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FEASIBILITY OF METRAC SYSTEM FOR REGIONAL AIR POLLUTION STUDY

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I. CONCLUSIONS

METRAC[TM] is an especially attractive technique to collect wind soundings of great accuracy and high-resolution in support of large field programs. Its feasibility has been adequately demonstrated in an urban environment during the Minneapolis field test. The accuracy and resolution apparent from the results of the field test suggest that the prototype system has a performance capability comparable to a radar tracking system. With minor modifications to the hardware and some development of software the present system can be employed to obtain wind soundings in support of the Regional Air Pollution Study Program. A further development effort will be required to incorporate temperature and humidity sensing capability into the system. Multiple tracking can be provided by duplicating parts of the system.

II. RECOMMENDATIONS

Because of a limitation of funding it was not possible to carry out the radar comparison test originally proposed for this feasibility study. A careful radar comparison test should still be made in order to further evaluate the accuracy and resolution capabilities of METRAC. Such a test should provide the information required to devise an optimal method to calibrate the system.

In order to realize the full potential of the METRAC system as an atmospheric probe, a further development effort will be required. Temperature and humidity sensors and modulation circuits should be added to the transmitter. Detector circuits for demodulation should be built into the receiver. Multiple tracking should be the goal of another development effort. This can be achieved by duplicating parts of the system.

III. INTRODUCTION

METRAC™ is a ground-based radio location system which employs the Doppler principle to track an inexpensive, lightweight, expendable transmitter. The transmitter can be attached to a vertically rising balloon in order to obtain an accurate, high-resolution, sounding of the atmospheric wind field. Alternatively, the transmitter can be attached to a horizontally free-floating balloon in order to determine atmospheric trajectories.

The METRAC system was originally conceived during the summer of 1965 as an economical means to obtain highly accurate wind data for air pollution studies. Since then, it has been under development by the Research Division of Control Data Corporation. Limited scale tests of the tracking system were performed in 1966 and again in 1969 verifying the principles of operation.

In 1969 the METRAC system was evaluated in competition with several other tracking systems by the MITRE Corporation (1969) under contract to ESSA. MITRE's effort under Project SESAME (System Engineering Study for Atmospheric Measurements and Equipments) provided information to assist Weather Bureau decision makers in selecting the basic vertical atmospheric sounding system for operation in the decade beginning in the early 1970's. For operational use MITRE recommended the NAVAID technique to the Weather Bureau since it had already undergone considerable development. The METRAC system was considered potentially superior in performance to the NAVAID systems but was not recommended because of the necessity of a costly research and development effort to implement the system.

Partly as a result of MITRE's report, Stanford Research Institute (1972) recommended the use of the METRAC system to the Environmental Protection Agency for its Regional Air Pollution Study (RAPS) Program. The present paper is the result of an evaluation of the feasibility of using the METRAC system for the RAPS program. For this reason results presented here are concerned primarily with low-level winds.

This report documents the results of a study conducted by Control Data Corporation to test the feasibility of employing the METRAC approach for collecting upper air data in support of the Regional Air Pollution Study (RAPS) Program being conducted by the Environmental Protection Agency in St. Louis.

The major portion of this report contains an engineering description of the prototype METRAC system that was fabricated for this feasibility study. The report concludes with a presentation of results from a field test conducted in Minneapolis by Control Data Corporation. This test consisted of a comparison of wind profiles obtained from METRAC with profiles obtained by simultaneously tracking the same balloon with a theodolite and a rawinsonde system.

IV. SYSTEM DESCRIPTION

A. Metrac System Description

The theoretical basis of METRAC and the electronics required to implement this system are not highly complicated. However, this system is a departure from commonly used tracking systems and its principles are sometimes confused. Therefore, a descriptive explanation of overall system operation is presented here.

The METRAC system is based on the Doppler shift of a moving transmitter. Although the physical principles are well known, only the recent availability of low-cost digital components and UHF-VHF transistors have permitted an economically feasible electronic design. METRAC uses omnidirectional antennas for both transmitting and receiving and does not require mechanical or electronic scanning. This eliminates the elaborate pedestal and drive assemblies and the limited capability under extreme environmental conditions associated with dish antenna tracking systems.

The basic elements of METRAC are an airborne transmitter and several receiving stations having known positions. As the transmitter moves in space, the frequency at each receiver equals the transmitted frequency plus a Doppler frequency shift, which is a linear function of the velocity of the transmitter. Because the true transmitted frequency may not be known, this Doppler shift cannot be determined from only the data at one receiver. However, the data from any pair of receivers permits a determination of the difference of received frequencies. Since these receivers are at rest with respect to each other, the frequency difference equals the difference of the Doppler shift associated with the receiver pair. This Doppler difference is the only data required to determine the transmitter position relative to the receivers.

The Doppler shift is a fundamental element of the METRAC system. The Doppler principle asserts that the received frequency of a signal is higher than the transmitted frequency as the transmitter moves toward the receiver. The received frequency is lower than the transmitted frequency as the transmitter moves away from the receiver. The received signals consist of the transmitted frequency, f_T, and a Doppler shift, d_i, where the subscript i refers to the receiver. The received frequency is then $f_T \pm d_i$. The transmitted frequency is not exactly known because the oscillator drift may be on the order of 10 KHz. This drift is significantly larger than the Doppler shift, which is less than 100 Hz for balloon tracking. The frequency difference for any receiver pair (i and j) is then

$$\Delta f = f_i - f_j = (f_T + d_i) - (f_T + d_j) = d_i - d_j \qquad (1)$$

Thus, the frequency difference is equal to the Doppler difference.

Since it is anticipated that the frequency difference for any receiver pair will be found using counters at each receiver site, the reception process can be simplified considerably by using a reference transmitter whose signal reaches all receivers in the system. The reference frequency f_R is then effectively subtracted from the received frequency indicated above, such that f_i becomes simply $f_T + d_i - f_R$. The frequency difference Δf between each receiver pair is unchanged, and remains equal to the Doppler difference.

The integrated Doppler difference associated with each pair of receivers is directly proportional to the slant range difference from the transmitter to each receiver. A known slant range difference determines a hyperbolic line of position on which the transmitter is located. The receivers are the foci of this hyperboloid. The data from three independent receiver pairs (four receivers) determines the transmitter position in space.

The electronics required to implement the system consists of an inexpensive balloon-borne transmitter, four or more receivers and a control station. These superheterodyne receivers are less sophisticated than good commercial FM receivers. The control station is used to record the Doppler data to determine the transmitter position.

A METRAC position determining system is illustrated in Figure 1. Variations in the position of a mobile transmitter are translated by the system into a computer generated output which gives detailed trajectory information. The functions of the system components are outlined in the following text.

1. Balloon Transmitter Function

The mobile transmitter, hereafter referred to as a balloon transmitter, transmits an unmodulated radio frequency carrier. Motion of this transmitter relative to a network of receivers will produce a shift in the received signal frequencies. The resulting Doppler shift information is recovered, combined with position data describing the location of receiver sites and the balloon transmitter at a known time, and then processed to generate the position information.

The transmitter operates at a frequency of 403 MHz. The operating frequency is crystal controlled to minimize the required receiving bandwidth and to permit the simultaneous tracking of multiple balloons. The effective radiated power

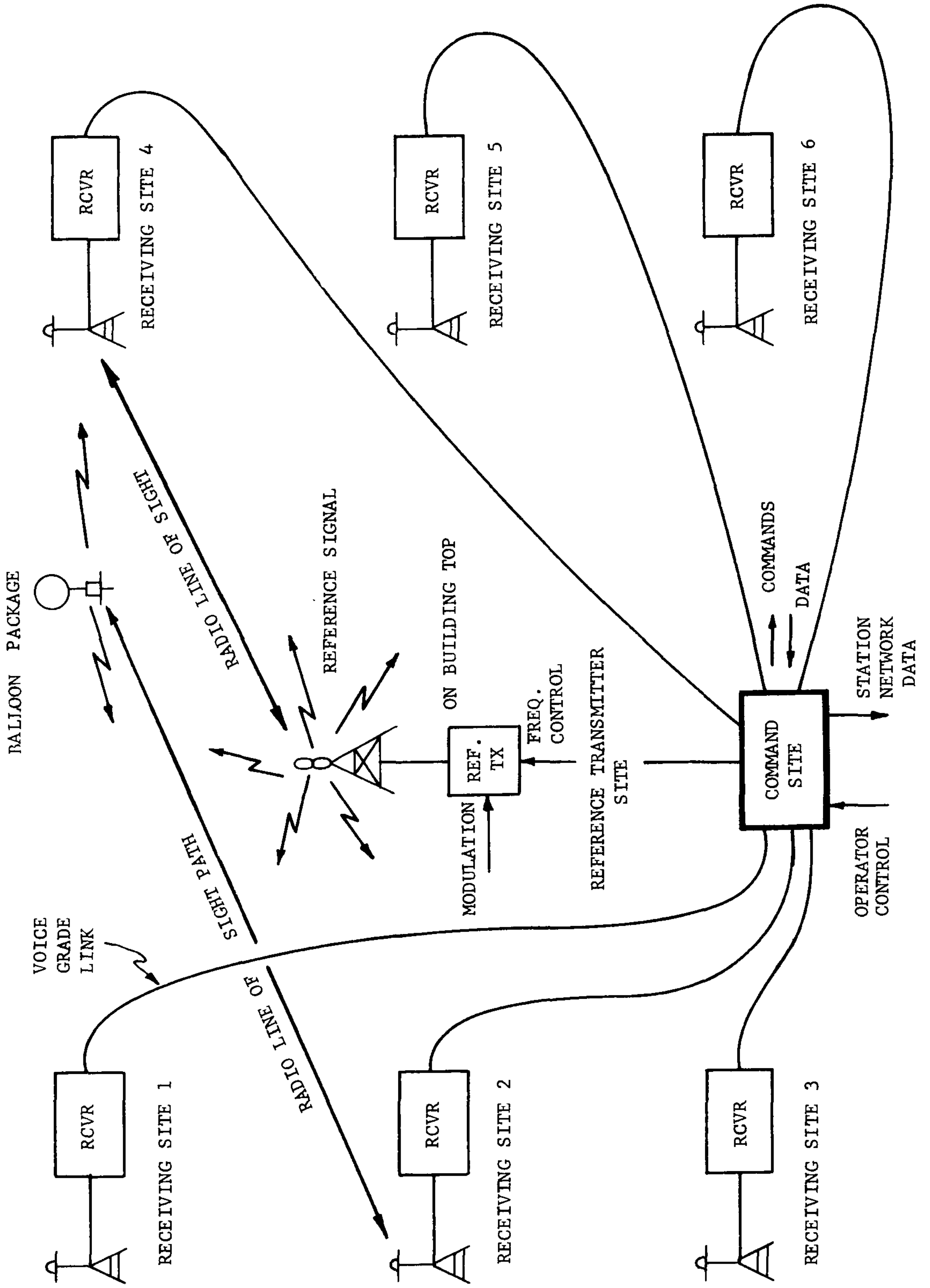


FIGURE 1. METRAC SYSTEM

output is 400 mW which provides an operating range in excess of 25 km. Vertical polarization is used to enhance multipath performance. The transmitter was designed as a reasonable cost, lightweight, expendable item. Total weight is less than 300 gms and the unpackaged volume is less than 24 cubic inches.

The transmitter package is subjected to a wide range of temperature in flights extending from the surface to the tropopause; the electronic circuits are designed to provide essentially constant characteristics over a $-30^{o}C$ to $+60^{o}C$ range. Packaging techniques extend this region to $-55^{o}C$ for flights of duration less than one-half hour.

2. Reference Transmitter Site Function

The reference transmitter site supplies two system functions. First, the reference transmitter eliminates the requirement that receiver sites measure the absolute frequency of the balloon signal. Instead, the receiver sites measure the difference in frequency between the reference and balloon signals. Second, the reference transmitter is phase modulated with a sine wave. All receiver sites recover this modulation to derive a constant frequency which permits improved sampling performance. This improvement results when the reference modulation signal is subtracted from the multiplied receiver signal. The use of multiplication increases the basic resolution of the Doppler measurement, and the offset by the reference modulation reduces the nominal receiver count rate F_{DO}, thus reducing sampling error.

The reference transmitter site provides a power output of 5 watts effective radiated power. This level insures an adequate reference transmitter signal at receiver sites such that difference frequency information will not be degraded due to reference channel noise and such that the reference transmitter modulation will have an adequate signal to noise ratio. To enhance the received signal, the antenna should have a line of sight path to all receivers. This requirement was satisfied in the Minneapolis test by mounting the reference antenna at the top of a 600 foot building (IDS Center).

System operation requires that the frequency of the reference transmitter must be adjusted to compensate for variations in the operating frequency of the balloon transmitter caused by changes in temperature and battery voltage. Such frequency variations are usually slow, long period, monotonic changes. This adjustment may be accomplished by manual control at the reference transmitter site or by remote control from the command site console. The use of remote control requires a voice bandwidth link from the command site. The reference transmitter frequency may be adjusted $\pm$ .005%; this is sufficient to accommodate the frequency changes caused by nominal and environmental balloon transmitter variations.

3. METRAC Receiver Site Function

A network of METRAC receiver sites is required to recover Doppler information. The METRAC receiver sites receive transmissions from the balloon and reference transmitters. The difference in frequency is extracted, then multiplied by eight to increase system position resolution. The multiplied frequency difference is offset by subtracting a constant frequency derived from reference transmitter modulation. This signal (FD_o) is accumulated in a digital counter. Status information describing the condition of receiver circuits and receiver signals is continually produced. Receipt of a sample command from the command site results in the transmission of a sample of the contents of the FD_o accumulator, the status information, and receiver ID.

The receiver is tuned by sweeping to acquire the reference signal. The command to acquire the reference is transmitted by the command site, and a single sweep of the receiver results, with a sweep duration of about 30 seconds. Once the receiver has acquired the reference, it operates with automatic frequency control to keep the reference acquired.

Another command permits clearing the FD_o accumulator to a count of zero. Commands from the command site and data to the command site are exchanged over leased telephone lines. The data are exchanged as eight bit characters. Asynchronous transmission of characters using 1200 baud modems is employed. The present METRAC receiver is constructed to operate over a 0 to 70^oC temperature range.

4. Command Site Function

The command site is the common data collection point in the METRAC system. The command site acquires data from all receiver sites. Data is recorded as sequential records on a cassette tape unit. After termination of a mission the cassette produced is played back to generate a CDC 6600 compatible tape.

The command site also provides control of the receiver site and reference transmitter site equipment. Commands transmitted to receiver sites permit acquiring the reference signal and zeroing of accumulators. Reference transmitter carrier may be turned on or off; frequency may be controlled manually or automatically.

System data output is monitored with a command site data monitor. The data displayed provides reference transmitter frequency control information and permits an evaluation of system performance. All system data is communicated over leased voice bandwidth telephone lines.

The data acquisition function requires the sampling of data at all receiver sites, the transmission of this data to the command site, and the formation of a sample record containing data from all sites. Ideally the FD_o accumulators in all METRAC receivers would be sampled simultaneously. This condition is approximated by simultaneously transmitting sample commands to all receiver sites. The time difference in receiver sampling results in a short term error of not more than one count per sample. No accumulative count errors from sampling uncertainty can occur.

The receiver sites transmit their data upon receipt of the sample command. Eight characters are used to represent station ID, the FD_o accumulator, status information, and space for sensor information. The command site stores this data in buffer registers. When data from all receivers has been stored, the registers are read out sequentially to form a single sample record of data from all receivers. This record is stored on a digital cassette recorder.

5. Minneapolis Site Function

The Minneapolis site generates a CDC 6600 compatible tape from the data recorded on the command site cassette unit. The command site tape can be transmitted over telephone lines to the Minneapolis site to produce an identical cassette tape. This cassette is played back, reformatted, and recorded on a 6600 compatible tape transport.

6. Computation Function

The tape containing receiver site frequency difference information and additional data describing receiver site locations and the balloon transmitter location at launch provide the input for trajectory computation. The computed output contains three dimensional position coordinates and velocities as a function of time. Additional output indicates system errors and the path taken to bypass these problem areas.

B. Data Format

The data sampled at each receiver is made up of eight 8-bit characters, and is appropriately termed a Receiver Sample. By simultaneous sampling of all receivers a complete record can be compiled containing data from each receiver for a given sample. This record is termed a Sample Record.

1. Receiver Sample Format

The receiver sample includes the following data:

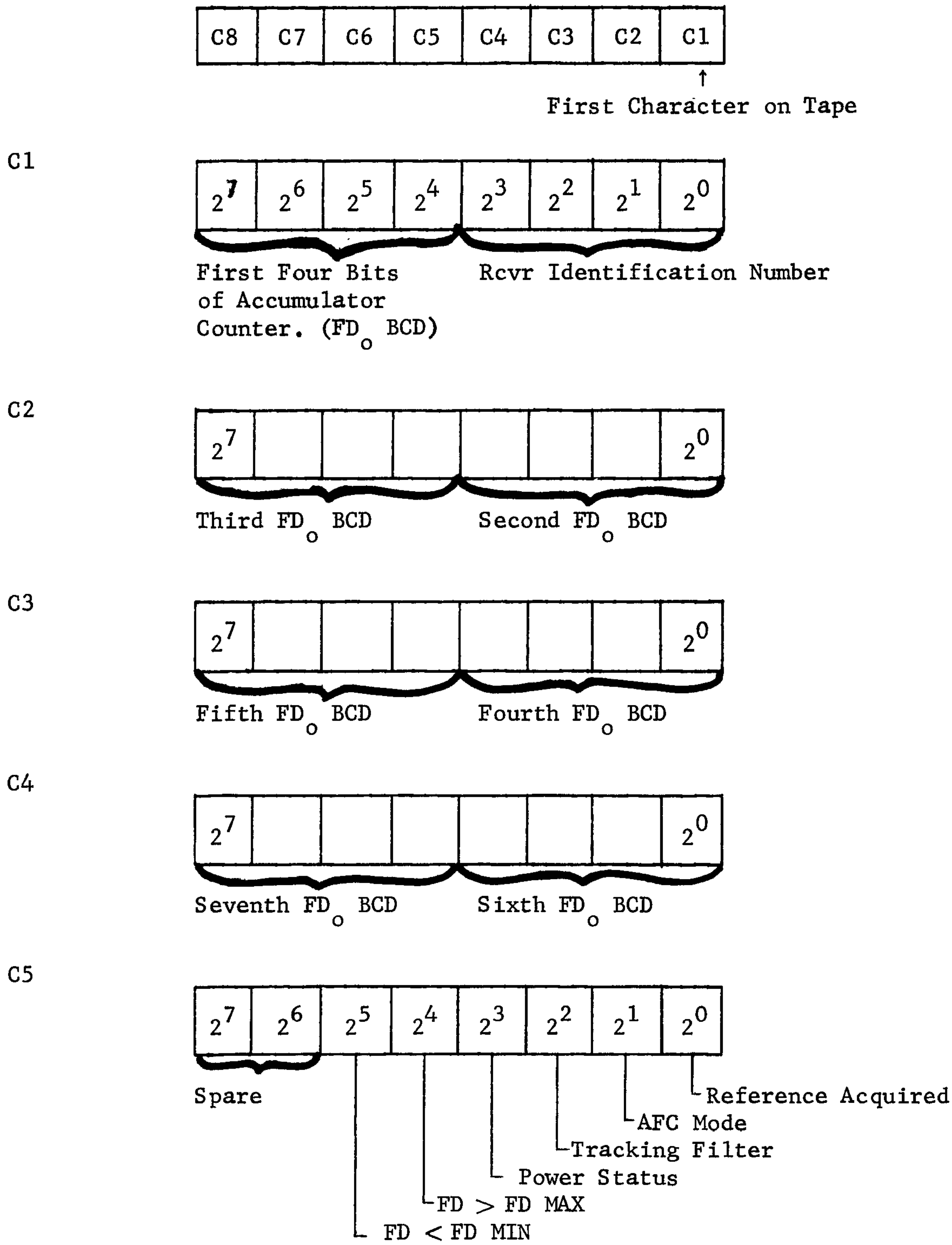
		Number of Bits
1.	Receiver Identification Number	4
2.	FD_o Accumulator Counter	28
3.	Status	8
4.	Sensor	24

The data is then divided into eight bit characters as shown in Figure 2. All data (except the ID) in the receiver sample is encoded in a BCD format. Thus, one decimal digit requires four bits of data such that two digits are packed into one eight bit character for transmission. The receiver ID is programmed for each receiver unit using hexidecimal representation. Seven decimal digits are used to represent the FD_O accumulator count. This requires twenty-eight bits of data. Status information is allocated eight bit locations, although only six are presently used. Twenty-four bits have been reserved for sensor data; this permits the transmission of two three-digit BCD numbers. These numbers might typically represent the temperature and pressure measurements from balloon-borne sensors.

The status information transmitted is defined in the following manner:

Bit Number	Name	Definition
1	Reference Acquired	Logic "1" indicates receiver is detecting the reference signal.
2	AFC Mode	Logic "1" indicates AFC circuit is in a track mode.
3	Tracking Filter Mode	Logic "1" indicates 2.8 KHz tracking filter is locked to an acceptable signal.
4	Power Status	Logic "1" indicates power is on.
5	FD > FMAX	Logic "1" indicates instantaneous frequency is greater than limit.
6	FD < FMIN	Logic "1" indicates instantaneous frequency is less than limit.
7,8	SPARES	

Bit positions 1-4 are normally at a logic "1". Bit positions 5-8 are normally "0". Deviation from this condition indicates data may be in error.



C6, C7, C8 all zeros

FIGURE 2: RECEIVER SAMPLE FORMAT

2. Cassette Tape Format

The cassette tape contains a series of Sample Records; one record is written for each sample period and each Sample Record contains a Receiver Sample for each network receiver site. The cassette is written incrementally with eight-bit characters as shown in Figure 3. The first character on tape is C1 (character 1) for the Receiver Sample of receiver #1. C2 through C8 are written, followed by C1 of receiver #2's data. After a complete Sample Record of 56 characters is written, a sync word containing 8 ones is written. A total of 57 characters (8 char/receiver x 7 receivers + one sync) is thus written for each Sample Record. The receiver record is derived as follows:

$$\frac{\text{Bits}}{\text{Sample Record}} = \frac{\text{448 Bits (Data)}}{\text{Sample Record}} + \frac{\text{8 Bits (Sync)}}{\text{Sample Record}} = \text{456 Bits/Sample Record}$$

Character = 8 Bits

8 Characters = Receiver Sample

7 Receiver Samples = Sample Record

Therefore:

$$\text{Sample Record} = \frac{\text{8 Char}}{\text{Receiver}} \times \text{7 Receivers} + \text{1 Char Sync} = \text{57 Characters}$$

3. 6600 Tape Format

The 6600 compatible tapes are made by grouping characters in groups of threes or 24 bits. Reformatting the data from three eight bit characters to four 6-bit frames gives the necessary conversion for 6600 processing. The format logic in the tape interface further divides the data to appear as follows:

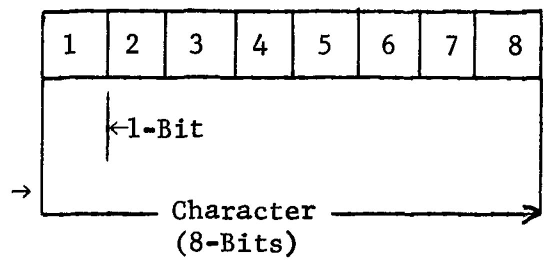
3 Characters = 24 Bits

Frame = 6 Bits

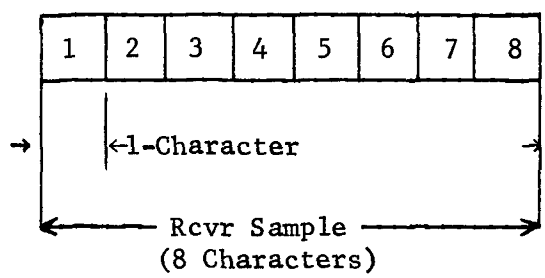
Sub-Character = 4 Frames

19 Sub-Characters = Record

1. CHARACTER



RECEIVER SAMPLE



SAMPLE RECORD

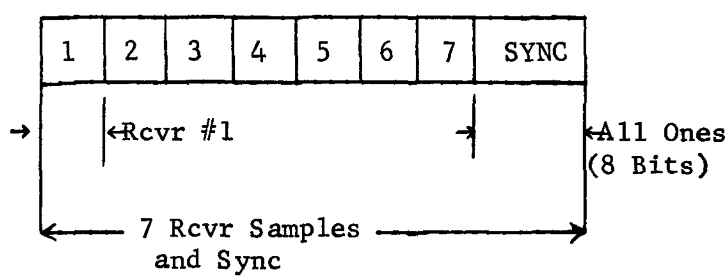


FIGURE 3: CASSETTE TAPE FORMAT

V. HARDWARE

A. Balloon Transmitter

The balloon transmitter design goal was to produce a compact lightweight, and reasonable cost expendable package. This package provides a crystal controlled radio frequency signal at 403.0 MHz with an effective radiated power level of 400 mW. The frequency is held to a tolerance of less than ± .005% and power is maintained essentially constant over a temperature range exceeding -30 to +60°C.

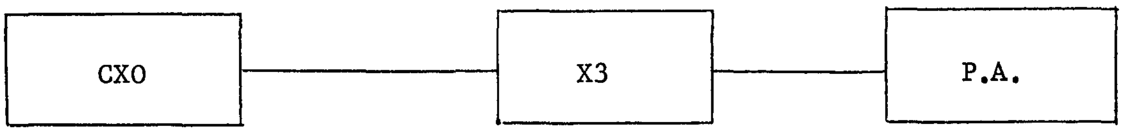
A picture of the packaged balloon transmitter appears in Figure 4. The package contains a battery pack, a R.F. section, and an antenna. The battery pack contains nine 1.5V cells wired in series with a battery connector. Transmitter power is enabled by attaching a mating connector from the R.F. section. The battery pack and R.F. section are assembled, tested, then encapsulated in a polyurethane foam. Finally, a water repellant cardboard covering is attached to the units.

A block diagram of the radio frequency section appears in Figure 5. Three functional blocks are present. The crystal oscillator used operates at 134.33 MHz; a seventh overtone crystal determines operating frequency. This oscillator is a commercially available module. The tripler stage contains a bipolar transistor operated as a grounded emitter Class C frequency multiplier. The base circuit is tuned to 134.33MHz and the collector circuit is tuned to 403.00MHz. The collector circuit provides impedance matching to the power amplifier stage containing a single bipolar transistor Class C amplifier. A double tuned circuit couples the amplifier to the load. More than 200 mW of load power is obtained at 50 ohms using a 13.5 VDC supply.

Bias to the tripler and amplifier stages is temperature compensated. The R.F. section is constructed on a teflon impregnated circuit board. Transmission lines etched on this material form the inductors for the resonant circuits. Air variable capacitors permit tuning these circuits.

The radiating structure for the transmetter is formed by a flexible quarter-wave element and the ground plane of the R.F. section and battery pack. The transmitter is normally operated in a vertical orientation, giving the pattern of a vertical dipole. Circuit pads are provided such that horizontal quarter-wave elements can be mounted. With capacitive connection to the transmitter output terminal, an elliptical polarization can be obtained, permitting operation with a transmitter directly above a receiving antenna.

FIGURE 4. PHOTOGRAPH OF PACKAGED BALLOON TRANSMITTER



FREQUENCY	403.000 MHz ±.005%
POWER	ERP ≈ 400 mW
SIZE	2 x 2 x 8" (Excluding Antenna)
WEIGHT	< 300 grams (Including Batteries)
TEMPERATURE	$-30^{o}C$ to $+60^{o}C$
ANTENNA	Dipole
SPURIOUS OUTPUT	≤ -36 dB relative to fundamental
D.C. POWER	13V @80 ma (≈1W)

FIGURE 5: BLOCK DIAGRAM OF TRANSMITTER RF SECTION

Figure 6 indicates the performance of a prototype METRAC balloon transmitter. The power output is strongly dependent on temperature below $0^{o}C$. The design was modified by incorporating temperature compensation of bias voltage. The resulting design was again tested versus temperature; results are shown in Figure 7. Power output is essentially constant to $-30^{o}C$.

Tests were performed in the METRAC laboratory to verify the performance of the balloon transmitter package with temperature and voltage variations. The package would operate with less than 1 dB of power degradation and acceptable frequency change for one-half hour after immersion in a $-50^{o}C$ cold box.

During several of the Minneapolis tests, an additional foam package was constructed of two inch polystyrene. This added insulation gave extended battery operation during the high level radiosonde comparison flights.

A shortcoming of the transmitter design is that only marginal drive is available at the power amplifier stage. This causes tuning to be somewhat critical. A further potential problem with the transmitter is the crystal itself. During tethered balloon tests it was found that sudden accelerations could cause relatively large changes in transmitter frequency. This effect was minimized by attaching the transmitter to the balloon using a cord attached to the antenna.

A period of faulty operation was noted for many flights. Each transmitter would experience a rapid frequency shift of several hundred cycles. This problem lasted perhaps one minute and was associated with balloon positions near the tropopause.

B. Reference Transmitter

The reference transmitter site performs two system functions. A) It provides a radio frequency signal located 2.8 KHz below the balloon transmitter frequency which is available at all receiver sites. By forming FD, the difference between

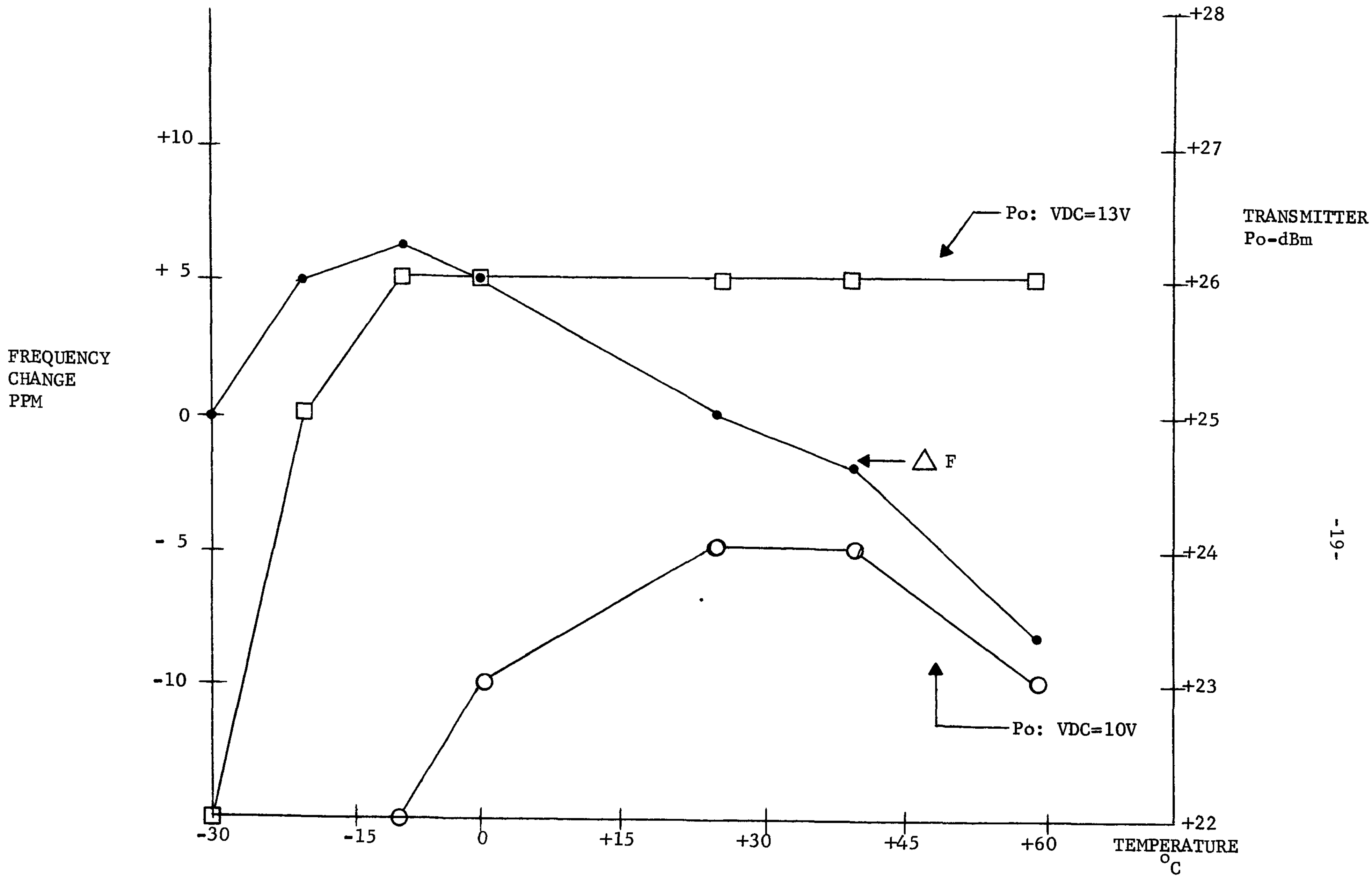


FIGURE 6: PROTOTYPE TRANSMITTER PERFORMANCE -VS- TEMPERATURE

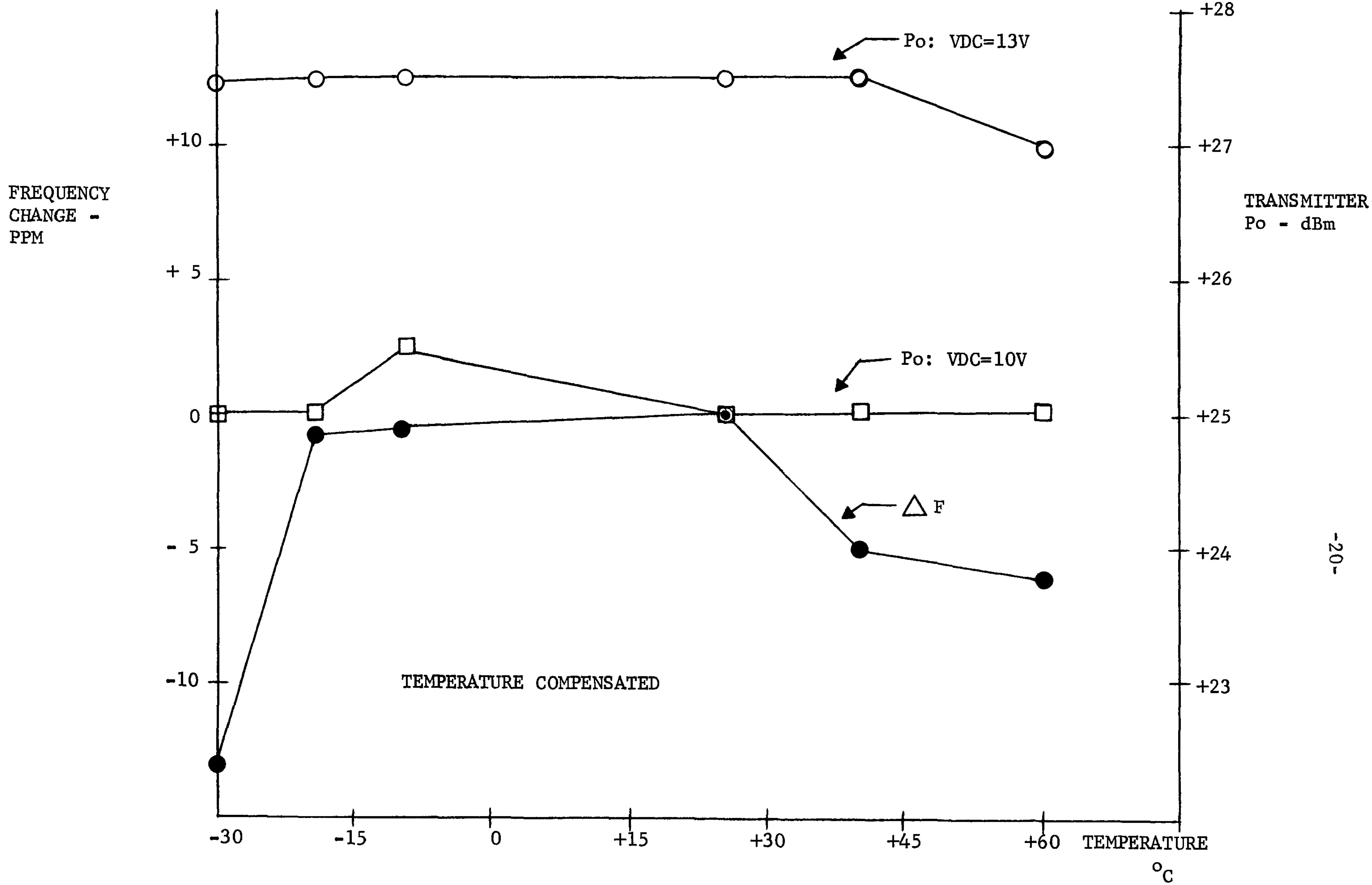


FIGURE 7: METRAC TRANSMITTER PERFORMANCE -VS- TEMPERATURE

balloon and reference frequencies, the Doppler difference formulation is made independent of receiver local oscillator frequencies. B) Transmitted reference modulation is available at all receiver sites. In the present system, this modulation permits a reduction in FD_o accumulator rate to reduce sampling error.

As the balloon transmitter frequency varies due to temperature and battery voltage changes, the reference transmitter must be adjusted to nominal 2.8 KHz offset to maintain normal receiver operation. Transmitted power level must provide sufficient receiver site signal so that: 1) the FD signal/noise ratio is not significantly degraded by mixing in the reference channel noise, and 2) the detected reference modulation has an adequate signal/noise ratio.

The present reference transmitter site generates a 5 W (ERP) signal. The frequency may be varied $\pm$ .005% from 403 MHz. The signal is phase modulated with a crystal oscillator derived 267 Hz sine wave. Figure 8 is a block diagram of the equipment.

The transmitter is provided with local and remote control of transmitter frequency and carrier (on/off). Locally, frequency is controlled with a ten-turn potentiometer. Carrier is turned on or off with a switch. The remote control mode of operation requires a telephone line link to the command site. Two narrow-band FSK tone channels decode command site control transmissions, while carrier on/off is controlled by a relay closure. A frequency to voltage converter translates tone modulation to develop the transmitter frequency control voltage.

The reference transmitter radio frequency chain contains a VCXO module, a phase modulator module, a tripler module, a power amplifier module, a tuned cavity, a transmission line, and an antenna. Transmitter frequency is determined by the

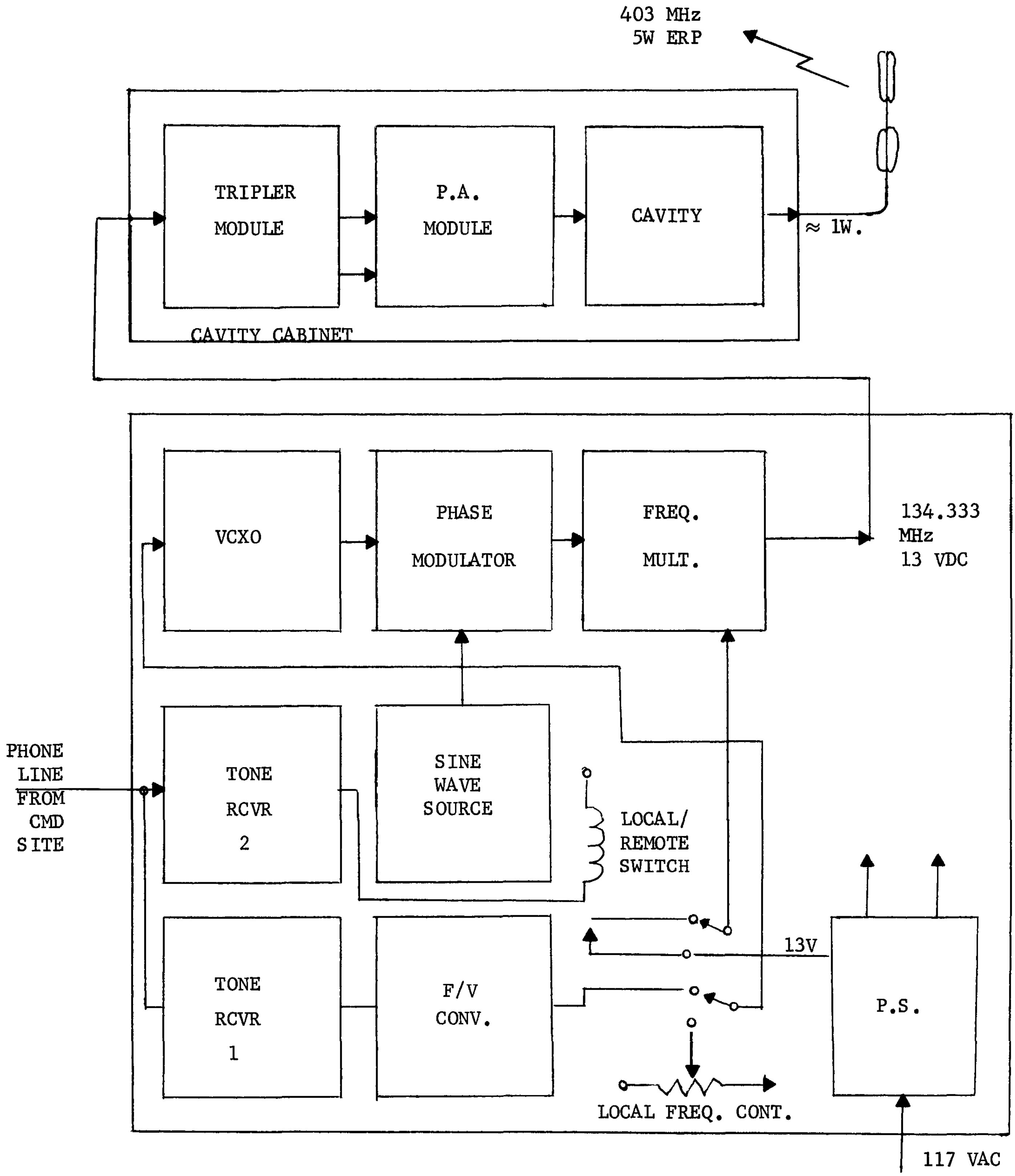


FIGURE 8: BLOCK DIAGRAM REFERENCE TRANSMITTER SITE EQUIPMENT

control voltage input to the VCXO module. The output of the voltage controlled crystal oscillator is phase modulated and then frequency multiplied to the module output frequency of 134.333 MHz. The frequency tripler module provides 403. MHz drive to the power amplifier module. The signal is filtered by the cavity, carried by the transmission line to the antenna, and radiated.

The VCXO module contains a fundamental mode crystal oscillator. The frequency is varied ± .005% for a 0-10V input voltage change which varies the bias of a voltage variable capacitance diode. The phase modulator is connected between this oscillator and two stages of frequency multiplication. These tripler stages provide a 134.333 MHz RF signal. A diplexing circuit combines DC power with this signal for transmission to the tripler module.

The phase modulator is designed to produce essentially ideal modulation characteristics. This is necessary to guarantee that modulation products will not cause interference at the balloon signal frequencies. The modulator peak phase deviation can be varied. The present METRAC system operates with a peak deviation of .3 radian.

The tripler module receives RF at 134.333 MHz and DC power through a 50 ohm transmission line. The two inputs are separated and the RF is tripled to 403 MHz. The DC powers both tripler and power amplifier modules. The frequency tripler function is realized using a modified METRAC balloon transmitter.

The power amplifier module provides power gain at 403 MHz. Greater than four watts of module output may be obtained. The power gain is varied with a potentiometer. A hybrid amplifier circuit, low pass filter, and power control circuit are contained within the module.

The tuned cavity is inserted in the system to reduce transmitter spurious output and to minimize interaction with neighboring R.F. sources. No intermodulation problem was detected during Minneapolis testing.

The transmission line used is a 50 ohm foam dielectric cable. Due to the power level, a braided shield cable was acceptable.

The antenna used is an omnidirectional gain type antenna, transmitting a vertically polarized signal. The antenna provides 8.9 dB gain referred to an isotropic source. The antenna gain permits obtaining the 5 watt ERP with moderate transmitter power and transmission line loss.

The modulating signal at the reference transmitter site is generated by the sine wave source card (SWS). The demodulation circuits at the receiving site have a narrow bandwidth (< 10 Hz) for noise performance; the modulating frequency must therefore be quite stable. The moderate separation of balloon and reference frequencies requires low harmonic content modulating signals. These two conditions are met by controlling the signal frequency with a crystal oscillator. Two cascaded active filters provide an essentially sinusoidal voltage output. The frequency produced may be changed by altering the division factor in a multistage frequency divider.

The reference transmitter electronic equipment is housed in two cabinets. A cavity cabinet contains the tripler module, power amplifier module and cavity. The VCXO module, phase modulator module, and power supply are housed in an instrument enclosure. A locked outer housing contains this enclosure and the remote control equipment. 117 VAC power is required to operate the system. A photograph of the tripler and power amplifier modules (Figure 9) shows the construction used. The cases used were designed to house CATV equipment in an outdoor

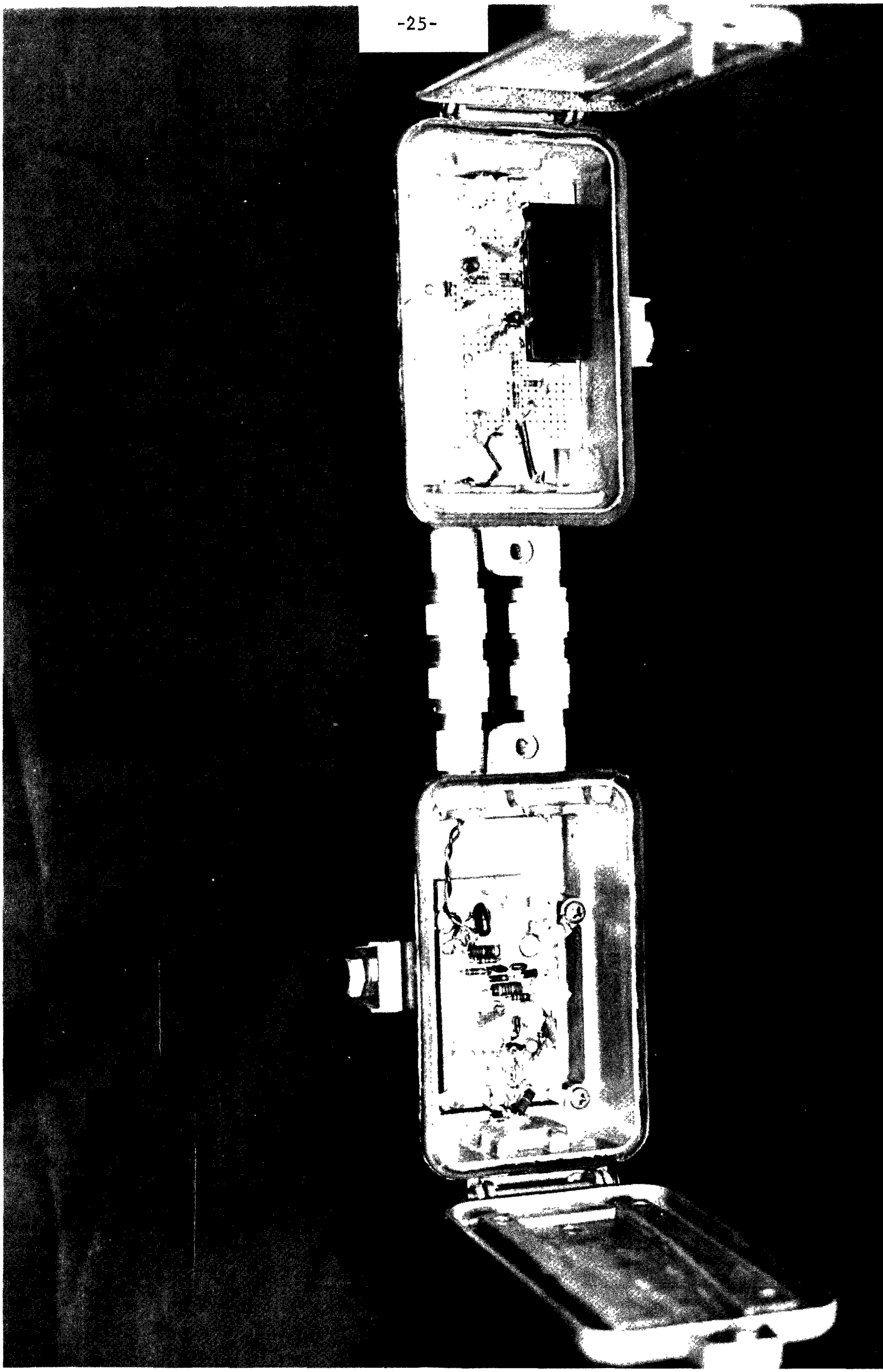


FIGURE 9. PHOTOGRAPH OF TRIPLER AND POWER AMPLIFIER MODULES

environment. This fact, coupled with the remote DC power capability mentioned, would permit mounting this equipment on a tower near the antenna. An additional photograph (Figure 10) shows the equipment enclosure used to mount the VCXO, phase modulator, and power supply. The modules are the same as those used for METRAC receiver construction.

C. Receiver

The METRAC receiver site monitors balloon reference transmitter signals and processes these signals to provide a digital message (receiver sample) which contains the Doppler difference information. The receiver sample further contains status information describing the condition of the receiver site equipment. It could also include information from balloon borne sensors. The receiver sample is encoded for transmission via voice grade telephone circuits. Commands initiated by the command site and communicated via these circuits are decoded to control the time of sampling of data, acquisition of the reference signal, and zeroing of receiver accumulators.

Figure 11 shows the three functional elements present at each receiver site; the RF, analog processing, and data acquisition sections. All components except the antenna, tower, transmission line, and cavity are housed within the receiver cabinet. The receiver sample can be monitored at the receiver site by connecting a receiver checkout unit to a test connector mounted on the front panel of the receiver cabinet.

1. Radio Frequency Section

The Radio Frequency Section contains: 1) antenna, tower, and transmission line; 2) the tuned cavity; 3) the RF circuits of the METRAC receiver.

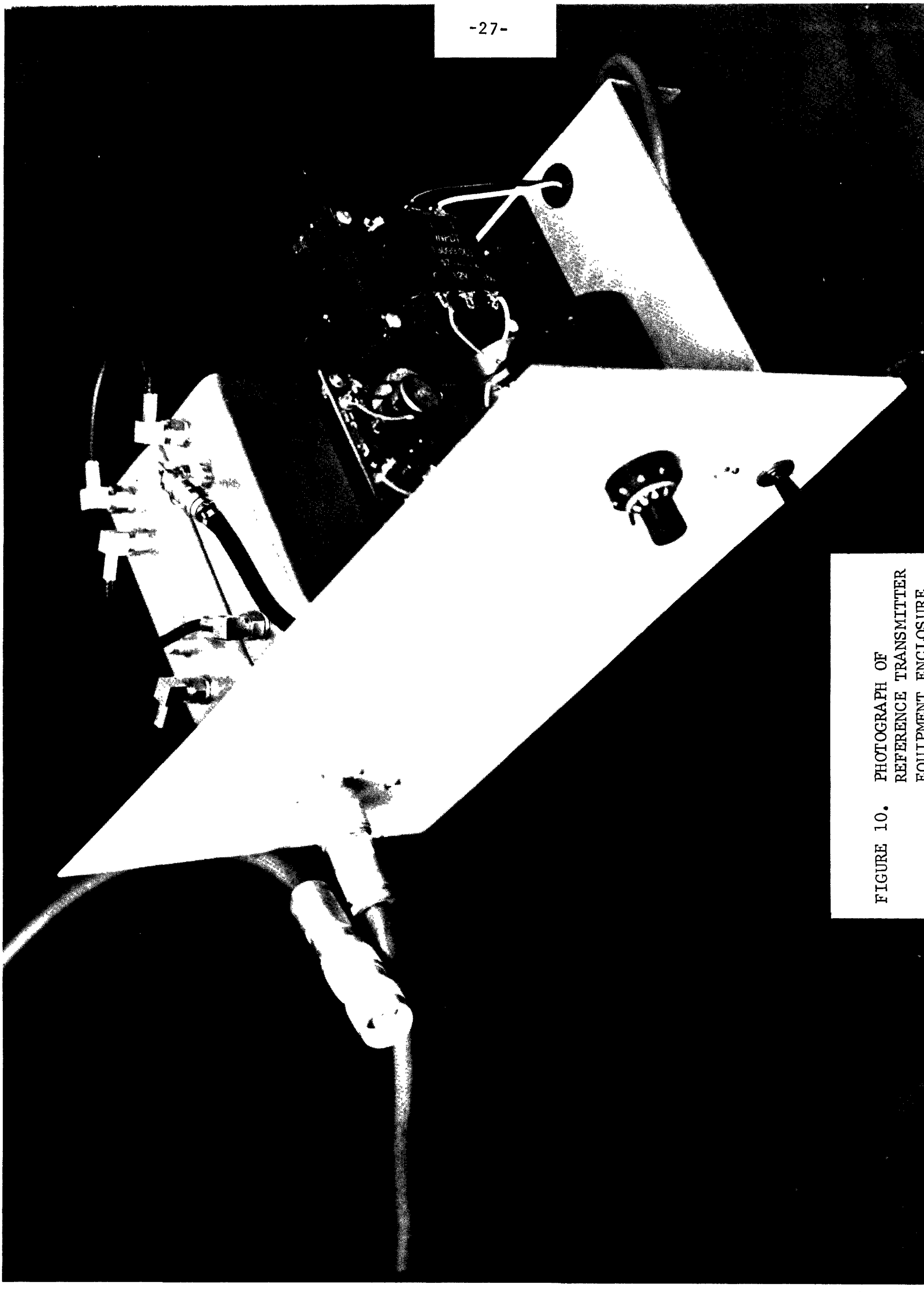


FIGURE 10. PHOTOGRAPH OF REFERENCE TRANSMITTER EQUIPMENT ENCLOSURE

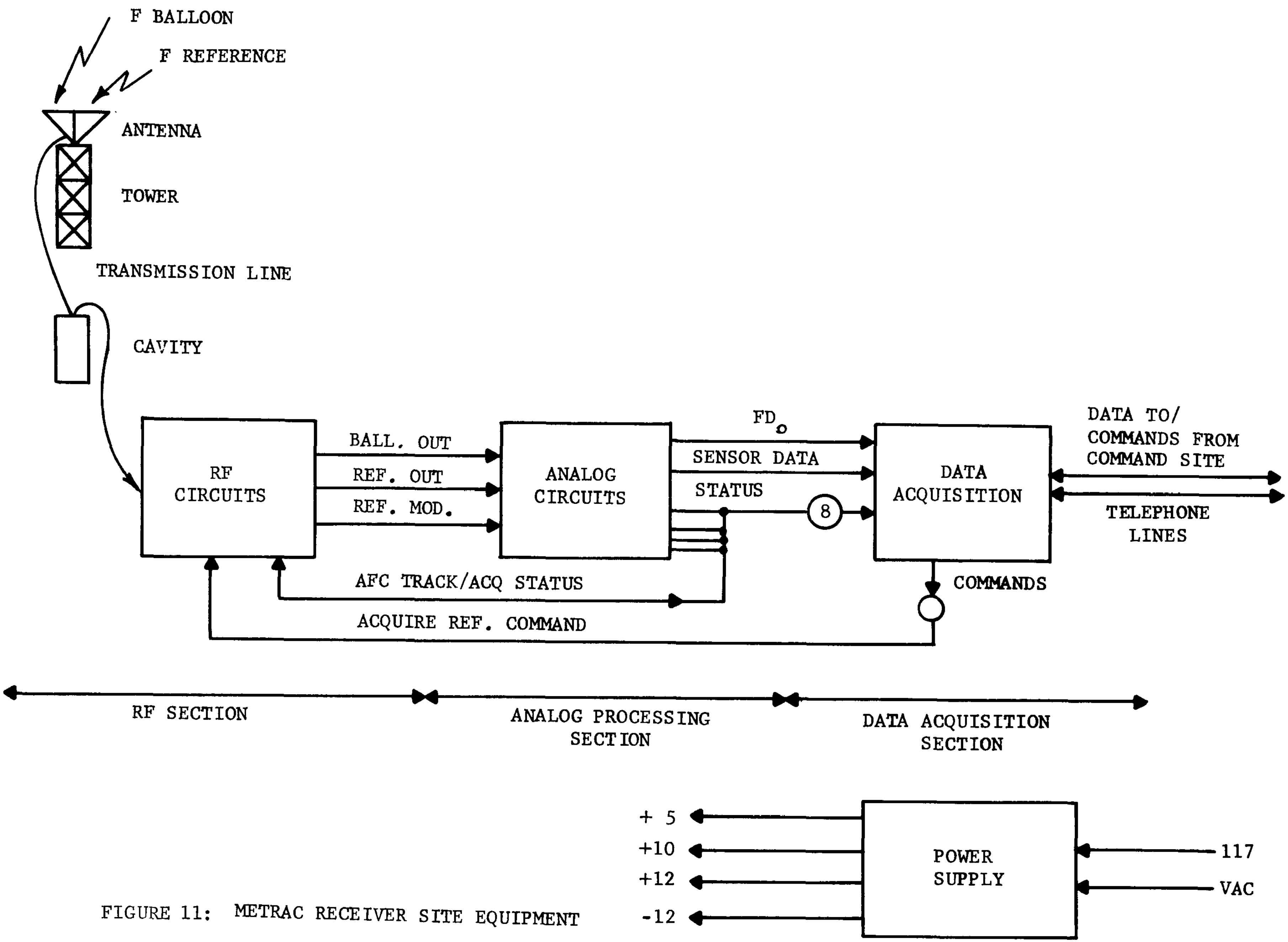


FIGURE 11: METRAC RECEIVER SITE EQUIPMENT

- Antenna, Tower and Transmission Line

The METRAC receiving antenna is a Right Hand Circularly Polarized (R.H.C.P.) antenna developed by the Andrew Corporation for reception of satellite transmissions. The antenna possesses a hemispherically shaped response pattern. Pattern gain is 0 dBiC at the horizon, + .5dBiC directly overhead, and -7 dBiC at 45^{o} below the horizon. The antennas measure 11 inches square by 15 inches high. A 12 inch stem below the antenna permits mounting.

If balloon transmitters are provided with circularly polarized antennas, tracking can be accomplished directly above a receiving site. Towers used in the METRAC system support the antenna and provide elevation above rooftops, etc., to improve multipath rejection for high elevation angles.

The transmission line used in METRAC is Andrew Corporation FHJ2-50A 50 ohm foam Heliax [R]; this is a solid conductor sheathed, foam dielectric cable. The attenuation at 400 MHz is 2.5 dB/100 feet.

The tuned cavity is a high-Q resonant circuit which provides additional selectivity preceding the RF circuits. This was required in our urban test to minimize effects due to local T.V. transmissions, UHF mobile radio transmissions, etc. The units were purchased from a commercial supplier and modified in the Research Division mechanical lab.

- RF Circuits

Figure 12 illustrates the RF circuits in the METRAC receiver. These circuits form a triple conversion superheterodyne receiver with automatic frequency control of tuning. Balloon and reference signals at 403 MHz are filtered to remove interfering sources, translated to 455 KHz, separated by highly selective filters, and amplified in limiting amplifiers. The balloon out and reference out signals are the inputs to the Analog Processing Section which contains the Doppler difference information; their difference in frequency is FD.

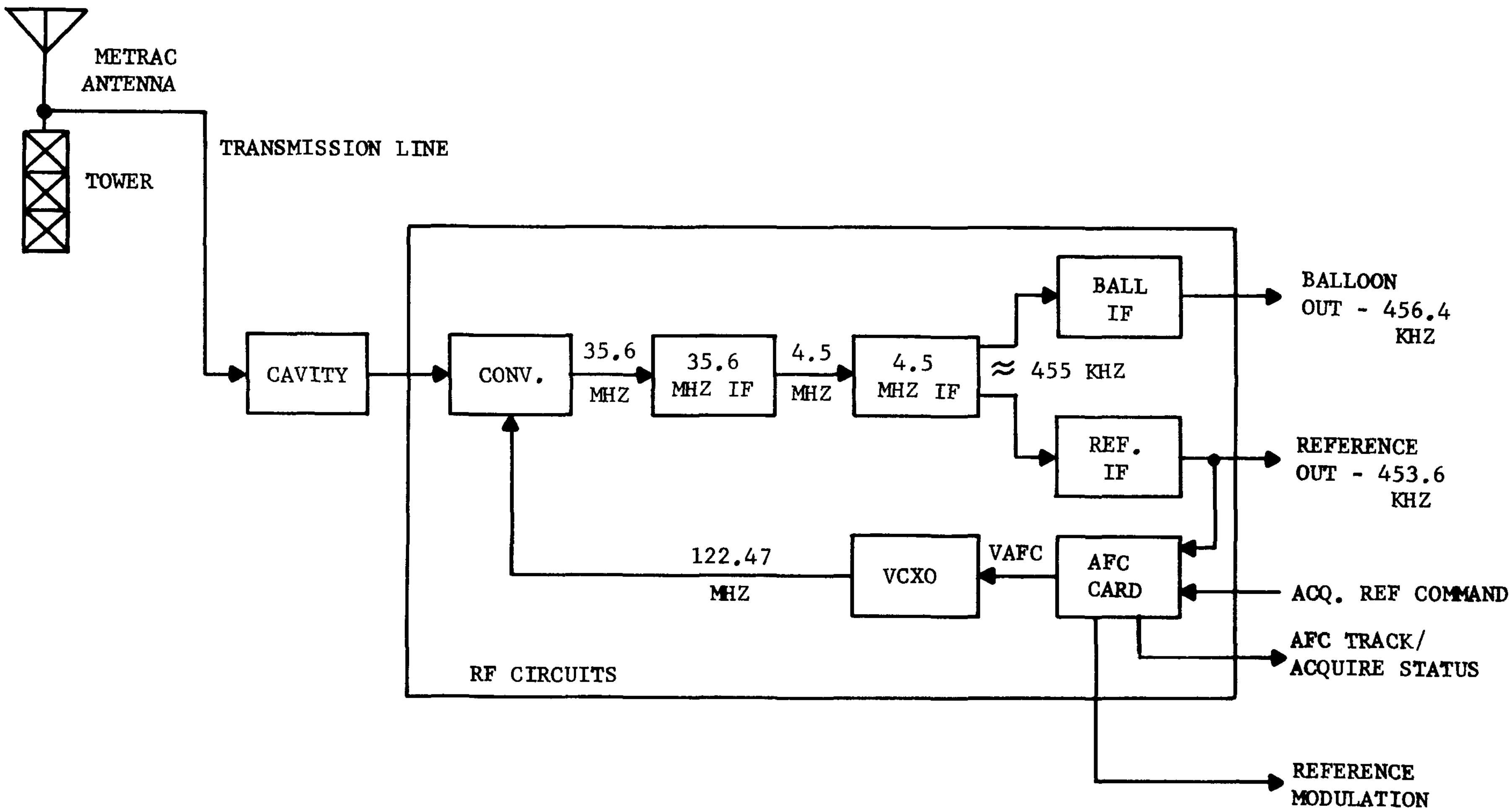


FIGURE 12: RF SECTION - METRAC RECEIVER SYSTEM

The receiver is tuned by varying the frequency of the local oscillator injection at the converter. The VCXO, which determines local oscillator frequency, is controlled by VAFC from the AFC card. Two modes of AFC operation are provided. Receipt of an "Acquire Reference" command from the command site or a receiver panel switch initiates the "Sweep" mode. Upon command the receiver initializes a frequency search from 402.980 to 403.020 MHz. Presence of an acceptable signal at reference out changes the "Reference Acquired" status bit to a logic 1 and sets the AFC mode to "AFC Track". The reference out signal now serves as the controlled variable in the AFC loop as the VCXO is tuned to maintain a constant reference out frequency.

AFC card status is transmitted by the Data Acquisition Section to the command site. "AFC Track" = logic 1 indicates the track mode. "Reference Acquired" = logic 1 indicates an acceptable reference signal is present. The AFC card also recovers reference transmitter modulation for use by the Analog Processing Section.

Several factors affected the design of the RF circuits:

1) METRAC is a differential system which requires the simultaneous reception of two R.F. signals.
2) METRAC utilizes non-directional receiving antennas.
3) The METRAC equipment is intended to operate unattended for relatively long periods of time.
4) In an urban environment the equipment would likely share antenna sites with other VHF/UHF communications equipment.

The differential nature of the system imposes the most stringent requirements. The balloon transmitter signal power detected at a receiver site located within one hundred feet of a balloon launch point could vary by > 80 dB. The reference signal will be fixed in amplitude but at a much lower power level, perhaps at the minimum useable level. To maintain linearity, minimal power gain ($\approx$ 30 dB) precedes the filters which separate the two signals.

Commercially available mechanical filters designed for single sideband radio applications were selected and used in METRAC for signal separation. These filters provide sufficient bandwidth (1.7 KHz) for the passage of balloon and reference modulation. Center frequency separation is small, 2.8 KHz, providing a moderate FD and permitting sampling with a voice bandwidth channel. A penalty associated with the frequency separation is that the balloon and reference modulation must be controlled to prevent splatter into the adjacent frequency range. Low index ($\beta \simeq .3$ to .5) phase modulation is compatible with this requirement.

The dynamic range requirement associated with the balloon signal, coupled with the expectation that angle modulation would be used in the balloon package to maximize carrier power and minimize modulator power requirements, led to the use of limiting amplifiers following the mechanical filters.

Omnidirectional receiving antennas operating in an urban environment (with attendant interference sources) motivated the decision to build a highly selective receiver. The requirement for long-term stability suggested that a triple conversion approach would be desirable. This approach also permits utilization of nearly optimum conversions in the mixing process. Image frequency rejection exceeds 70 dB in each conversion, while spurious product rejection approaches 70 dB. Figure 13 shows RF Circuit Specification.

- <u>Converter</u>

The converter accepts balloon and reference signals at 403 MHz, filters and amplifies these signals, and translates them to 35.6 MHz. A conversion power

FIGURE 13. RF CIRCUIT SPECIFICATION

SIGNAL INPUT:	Impedance = 50 ohms Noise Figure = 3-5 dB Frequency Tuning Range = 402.980 to 403.020 MHz (403 MHz ±.005%)
SIGNAL OUTPUT:	IF Bandwidth = 1.7 KHz Nominal Output Level = 1 V p.p Nominal Output Frequency = 453.6 KHz (Reference) 456.4 KHz (Balloon)
DYNAMIC RANGE:	15 dB S/N at -120 dBm 1 dB Compression -30 dBm Balloon/Reference Differential ≤ 50 dB
TUNING:	Track Mode - Reference out maintained at 453.6 KHz ±40 Hz Sweep Mode - Searches 402.980 - 403.020 MHz
SPURIOUS RESPONSE:	Image Rejection ≈ 70 dB

gain of 25 dB is obtained with an input noise figure of 3 to 5 dB. Two stages of R.F. gain precede the mixer. The mixer local oscillator injection at 367.4 MHz is developed by a transistor tripler driven by the 122.4666 MHz output of the VCXO module.

Image frequency rejection is in excess of 70 dB. Spurious responses caused by the non-fundamental local oscillator injection are down $\simeq$70 dB with a tuned cavity in the input signal line. One dB of signal compression occurs at an input signal level $\simeq$-35 dBm.

The converter used is a modified commercial unit developed by Vanguard Laboratories. Modifications included the addition of shielding to improve tuning stability, the change to accept drive from the VCXO, and minor mechanical changes to provide compatibility with the receiver packaging system.

- 35.6 MHz IF

This IF is driven by the converter; signals are filtered and translated to 4.5 MHz. A power gain of about 5 dB is obtained, along with a noise figure of 18 dB and an image frequency rejection of 70 dB. The module contains a 1.5 MHz bandwidth three pole filter, a MOSFET mixer, and a 31.1 MHz crystal oscillator. The units were designed, assembled, and tested by Control Data.

- 4.5 MHz IF

The signal input at 4.5 MHz is filtered and translated to 455 KHz. Low impedance outputs are provided to drive the balloon and reference IF strips. A power gain of 5 dB is obtained, along with a noise figure of 12 dB and an image frequency rejection of 70 dB. The filter function provides an RF bandwidth of 200 KHz. An MOSFET mixer driven by a crystal oscillator performs the frequency translation.

- Balloon I.F.

Signals at 456.4 KHz $\pm$ 850 pass through a highly selective mechanical filter. Cascaded amplifier and limiter stages provide a nominal output signal of IV p-p for receiver inputs in excess of -120 dBm. Module power gain is $\simeq$ 107 dB.

The mechanical filter used provides the rejection of the reference signal required for system operation. The units provide > 65 dB rejection. The amplifier is constructed using 3 voltage gain stages with broadband crystal filter interstage coupling. The first stage contains a low noise discrete transistor. The second stage uses an integrated circuit limiting amplifier. The third stage is also an I.C. limiter; an emitter follower drives the output connector to provide isolation and a low impedance output.

These units were designed, constructed, and tested at Control Data. Satisfactory operation was obtained but with some difficulty due to the fact that about 110 dB of power gain is contained within the package.

- Reference I.F.

These circuits are similar to the balloon I.F. except that the signal frequency is 453.6 KHz $\pm$ 850 Hz.

- AFC Card

The AFC card controls receiver tuning by varying the VAFC tuning voltage to the VCXO module. The card operates in either a track or sweep mode; the sweep mode being associated with the acquisition of the reference signal. An "Acquire Reference" command decoded by the data acquisition section (or initiated by a receiver panel switch) sets the AFC card in the "Sweep" mode. VAFC then increases from 0 to 10V, tuning the receiver from 402.980 to 403.020 MHz. Detection of an acceptable reference signal causes a "Reference Acquired" indication. This transition initiates the "Track" mode of operation. The reference out signal frequency becomes the controlled variable in an AFC loop formed by the AFC card, the VCXO module, the converter, 35.6 MHz and 4.5 MHz I.F.'s, and the Reference I.F. VAFC is varied to maintain the reference out signal at 453.6 KHz. The "Reference Acquired" and "AFC Track" indications are two of the status bits transmitted by the data acquisition section to the command site.

The AFC circuitry is designed to be stable and accurate, maintaining the reference out frequency within ± 50 Hz of nominal with transmitter frequency variations of ± 20 KHz. The reference output signal at 453.6 KHz is the signal input to a mixer located on the AFC card. A 450 KHz crystal oscillator provides the local oscillator signal. The mixer output at 3.6 KHz drives two circuits: a narrowband tone detector and a frequency discriminator. The narrowband tone detector initiates a "Reference Acquired" indication when a signal is present at 3.6 KHz ± 180 Hz. The frequency discriminator produces a voltage proportional to signal frequency. This voltage is filtered to drive an error amplifier. When operating in the "Track" mode this error voltage is amplified to produce VAFC. VAFC in the Sweep mode is produced by a ramp voltage generator. An FET Analog multiplexer selects the source which develops VAFC.

The voltage output of the frequency discriminator also recovers frequency modulation for use by the analog processing section.

- VCXO

The VCXO module is the voltage variable frequency source in the METRAC receiver. VAFC variation from 0-10V tunes the receiver from 402.980 MHz to 403.020 MHz. The module output is a 122.466 MHz sine wave at a power level of 10 mW.

To directly obtain frequency variations of $\pm$ .005% from a crystal oscillator it is necessary to use a fundamental crystal. This fundamental signal is multiplied by cascaded frequency multipliers to obtain the desired output frequency. The fundamental crystal oscillator is tuned with a voltage variable capacitance diode. Oscillator output is doubled, then tripled to the output frequency. A double tuned output filter circuit is used to minimize spurious receiver responses due to local oscillator products.

2. Analog Processing Section

The analog processing section accepts the constant level balloon and reference output signals. The difference frequency (FD $\simeq$ 2.8 KHz) is formed, then filtered to reduce the noise bandwidth to $\simeq$ 400 Hz. The FD signal is then multiplied by a factor of eight resulting in MXFD at $\simeq$ 22.4 KHz. Finally, the MXFD signal is offset by a constant factor to produce FD_o at $\simeq$ 5 KHz. The FD_o signal which contains multiplied FD information then increments the data acquisition section FD accumulator. An FD monitor circuit generates status error information when receiver S/N is not adequate for reliable operation.

The bandwidth obtained with the mechanical filters is excessive in terms of the signal bandwidth required by the received R.F. carriers. Further, a METRAC system simulation indicated a multiplication of Doppler difference information would be required to obtain resolutions comparable with initial estimates. This requisite multiplication also indicates that a reduction in bandwidth is in order.

The 2.8 KHz tracking filter was inserted to provide the desired reduction in effective bandwidth. The filter's 3 dB bandwidth was set at 200 Hz. The uncertainty in the frequency difference suggested using a phase locked loop to provide the filter function. The loop would track the difference frequency as the quantity varied. The tracking filter also contains a sweep circuit and a lock detector. These components were added to permit acquisition of the signal as the tracking bandwidth was insufficient to permit loop capture for difference frequency variations of $\pm$ 800 Hz. The lock detector determines if the filter is locked to the input signal.

A monitor circuit was also designed into the analog processing circuits to monitor received signal quality by examining the signal present at the output of the FD difference circuit. Because of the limiting I.F. amplifiers, amplitude variations have been removed from the signals; therefore, the frequency characteristics only are monitored. Frequency deviations exceeding $\pm$ 1.4 KHz are detected to set error indicating latches. The phase deviation associated with this indication is about $\pm 90^{\circ}$. An error indication does not guarantee an error in accumulation has occurred, but indicates the received S/N ratio is in question.

The FD multiplier circuit was designed to provide a variable multiplication factor. The factor of eight presently implemented is a compromise between increasing the quantization resolution and decreasing the signal to noise ratio at the accumulator. The circuit was designed to have a signal bandwidth sufficient to pass FD signals at 2 through 3.6 KHz. The output frequency for a nominal FD is $\simeq$ 22.4 KHz.

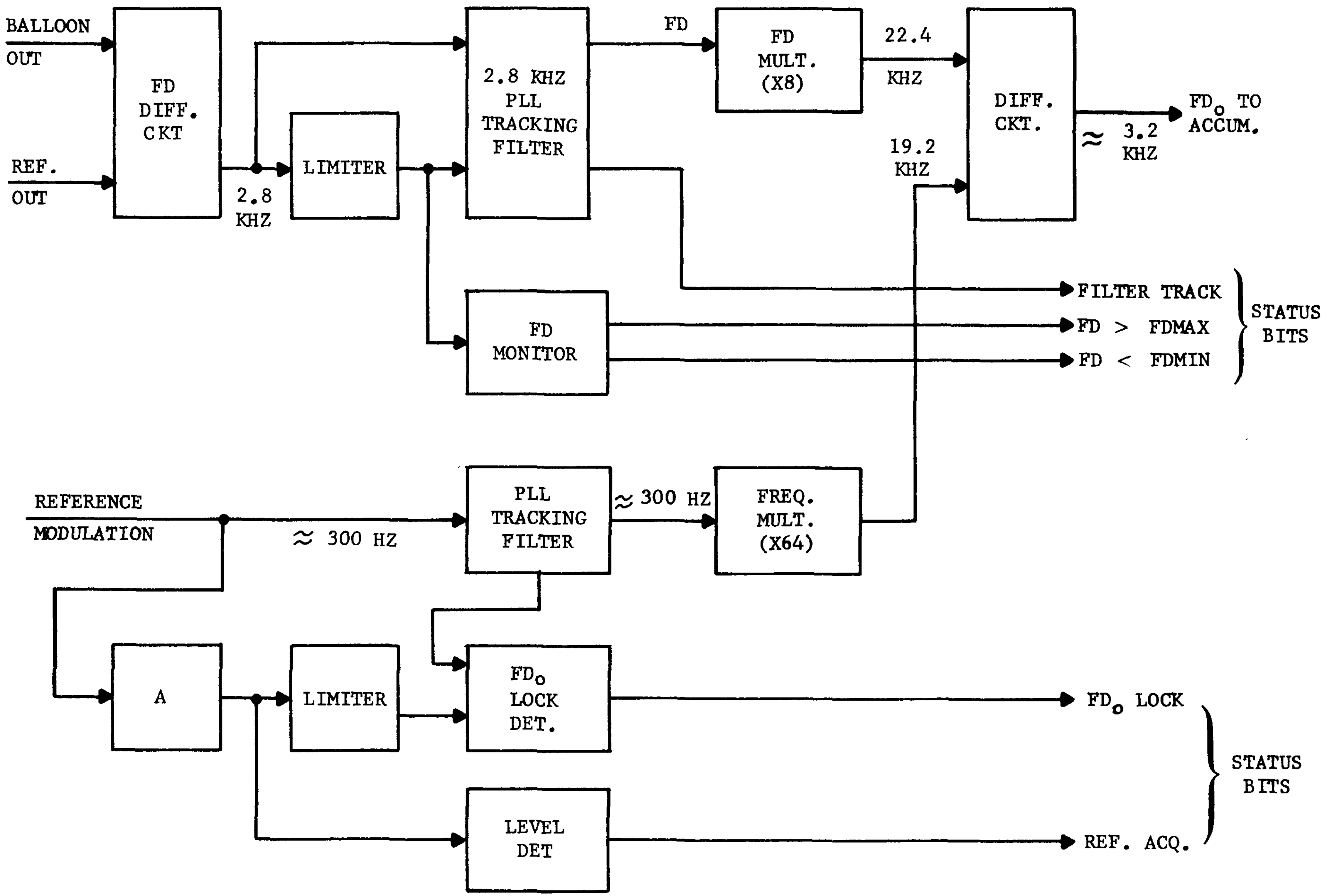
The 22.4 KHz rate resulting from the addition of the FD multiplier circuit required the addition of an FD offsetting circuit. This circuit subtracts a constant frequency from the multiplied FD. The Doppler information is retained, but the rate of accumulation is reduced which results in reduced sampling errors for a fixed sampling time uncertainty. The offsetting frequency used must be identical at all receiver sites to prevent the accumulation of a count difference between receivers. Accordingly the offsetting frequency is derived from reference transmitter modulation. Low frequency ($\simeq$ 268 Hz) sinusoidal modulation is compatible with system requirements to minimize interaction between the reference and balloon signals. Detected modulation is filtered to reduce frequency uncertainty and then multiplied to $\simeq$ 17 KHz. Subtracting this constant from 22.4 KHz resultings in a offset frequency difference (FD_o) signal at 5 KHz. A factor of five reduction in sampling error results.

Figure 14 shows the block diagram of the Analog Processing Section; constant level balloon out (456.4 KHz) and reference out (453.6 KHz) signals are differenced by the FD Difference Circuit to produce FD ($\simeq$ 2.18 KHz). The FD signal is filtered by the 2.8 KHz phase lock loop tracking filter, then multiplied by eight in the FD multiplier circuit, to produce MXFD (22.4 KHz). The FD_o difference circuit differences MXFD and a 17 KHz signal derived from reference modulation. The output FD_o containing the multiplied Doppler difference information increments the Data Acquisition Section FD accumulator.

Additional Analog Processing Section outputs are status bits. The FD monitor continuously examines the output of the FD difference circuit. An instantaneous deviation in FD beyond preset limits sets error latches. Status bit "FD > FMAX" indicates that FD exceeded the upper frequency limit during a sample interval whereas the "FD < FMIN" status bit indicates that FD was less than the lower frequency limit.

The P.L.L. tracking filter status is indicated by the "Filter Track" status bit; logic 1 indicates that the FD signal is acceptable and is being tracked by the loop. Logic 0 indicates the tracking filter center frequency is being swept to locate an acceptable signal.

The FD difference circuit contains a linear multiplier to mix the balloon and reference signals and a bandpass filter to recover the difference frequency component. The bandpass output drives a limiter and the 2.8 KHz P.L.L. tracking filter. The limiter output drives the FD monitor which generates the "FD > FMAX" and "FD < FMIN" status bits.



RF SECTION

FIGURE 14: ANALOG PROCESSING CIRCUITS

The 2.8KHz tracking filter was required to permit FD multiplication without a drastic increase in the system signal/noise requirement. The filter contains a phase locked loop providing a bandwidth of 200Hz, a lock monitor, and a sweep circuit. The lock monitor controls the mode of loop operation; if frequency lock is maintained between the loop and the FD signal, a "Filter Track" indication is produced. If frequency lock is not maintained, the mode changes to sweep. The sweep circuit varies the center frequency of the P.L.L.; when frequency lock is established, the mode reverts to track.

The Analog Processing Section functions are contained on three circuit cards; the FD difference circuit, limiter, and 2.8KHz tracking filter are on one card. The FD monitor and FD multiplier are on a second card, while the P.L.L. tracking filter, multiplier, and FD_o difference circuit form a third card.

The various components required at a METRAC receiver site are illustrated in a series of photographs. Figure 15 is a picture of the METRAC receiving antenna and tuned cavity. Figure 16 shows the METRAC receiver front panel. Front panel connectors are used for telephone line connections, the RF input cable, the receiver checkout unit, and for AC power.

The receiver was mechanically designed to permit rapid access to all components; Figure 17 illustrates the interior of the receiver. The RF circuits are housed in modules developed by CDC. Signal connections are made using co-axial cable and mating R.F. connectors while power is supplied to the modules through pins mating with chassis connectors. The analog processing circuits (not shown) and the data acquisition logic are mounted on printed circuit cards and plugged into a card rack; spare slots are provided for the addition of circuitry to recover sensor information. All major components can be removed in a few moments.

The modules used for the RF circuits are shown in Figure 18, in which the outer shield has been removed. Rapid access is provided.

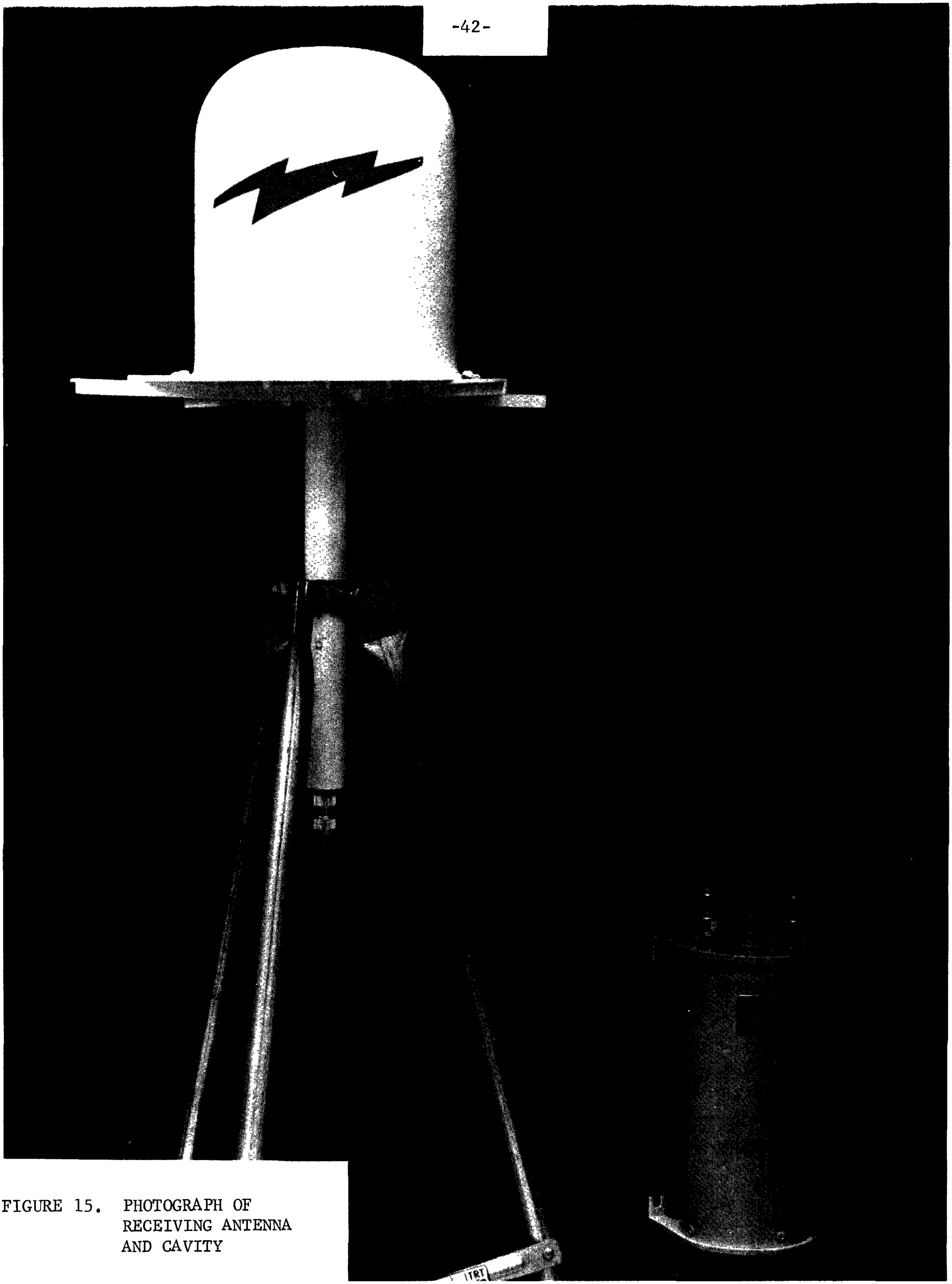


FIGURE 15. PHOTOGRAPH OF RECEIVING ANTENNA AND CAVITY

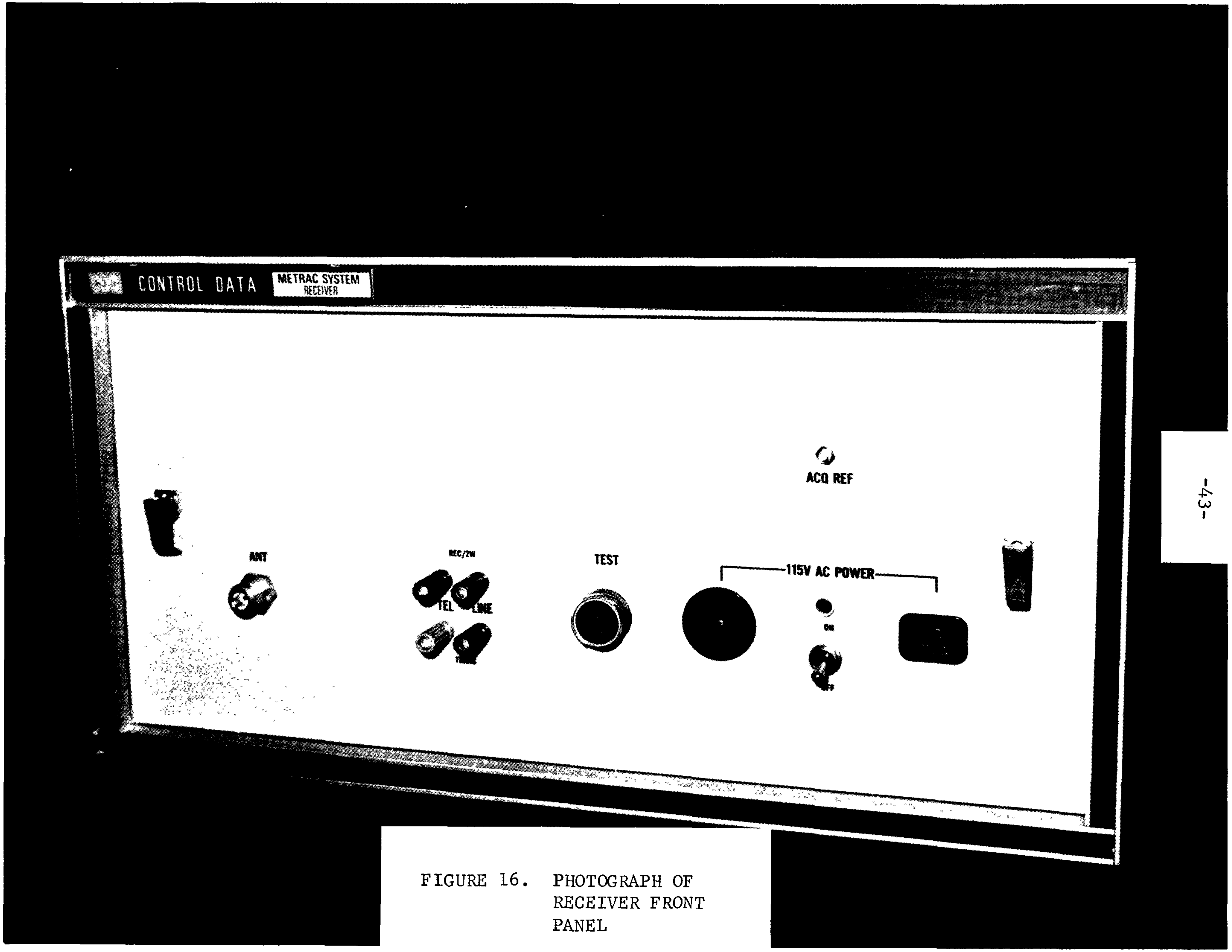


FIGURE 16. PHOTOGRAPH OF RECEIVER FRONT PANEL

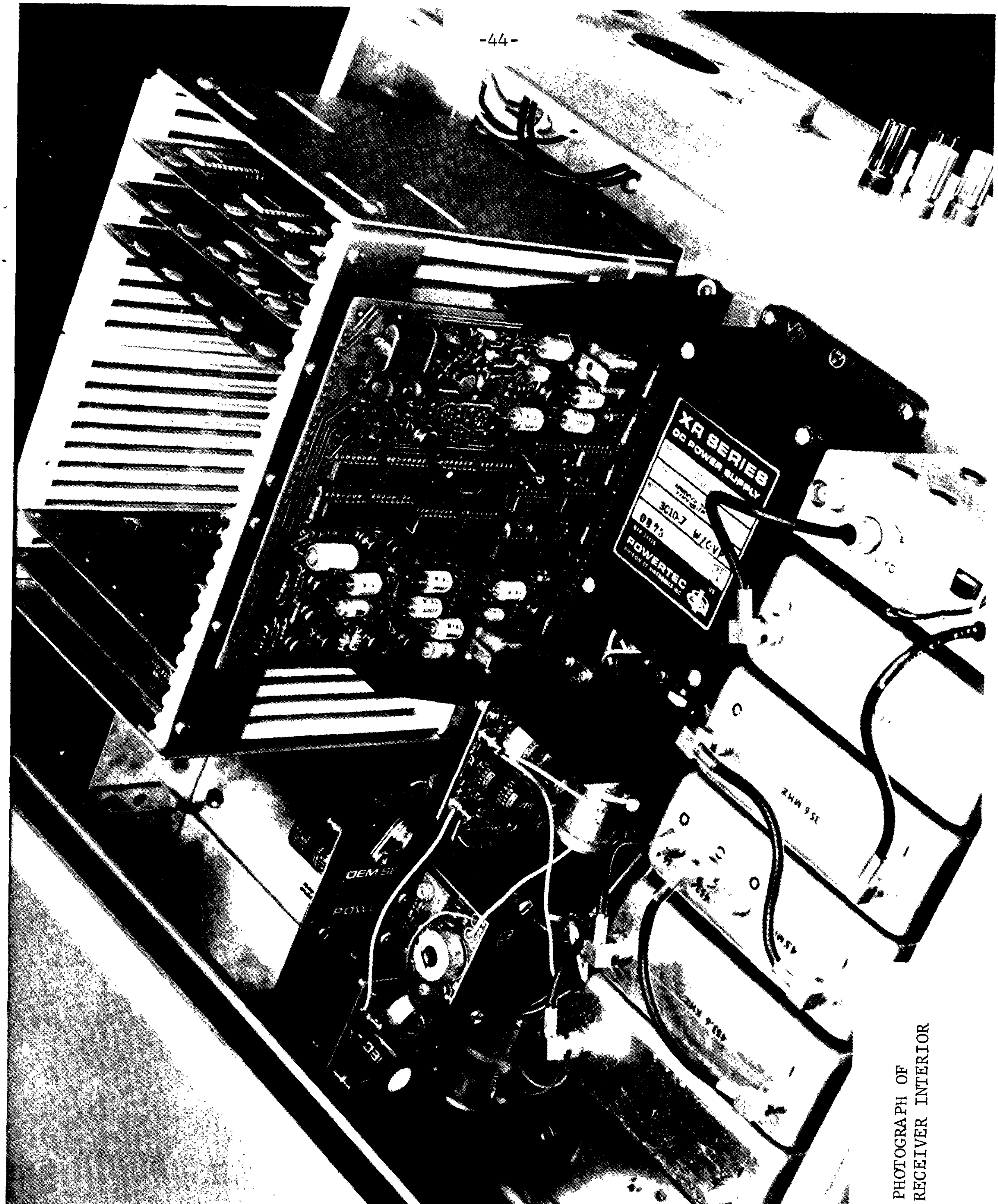


FIGURE 17. PHOTOGRAPH OF RECEIVER INTERIOR

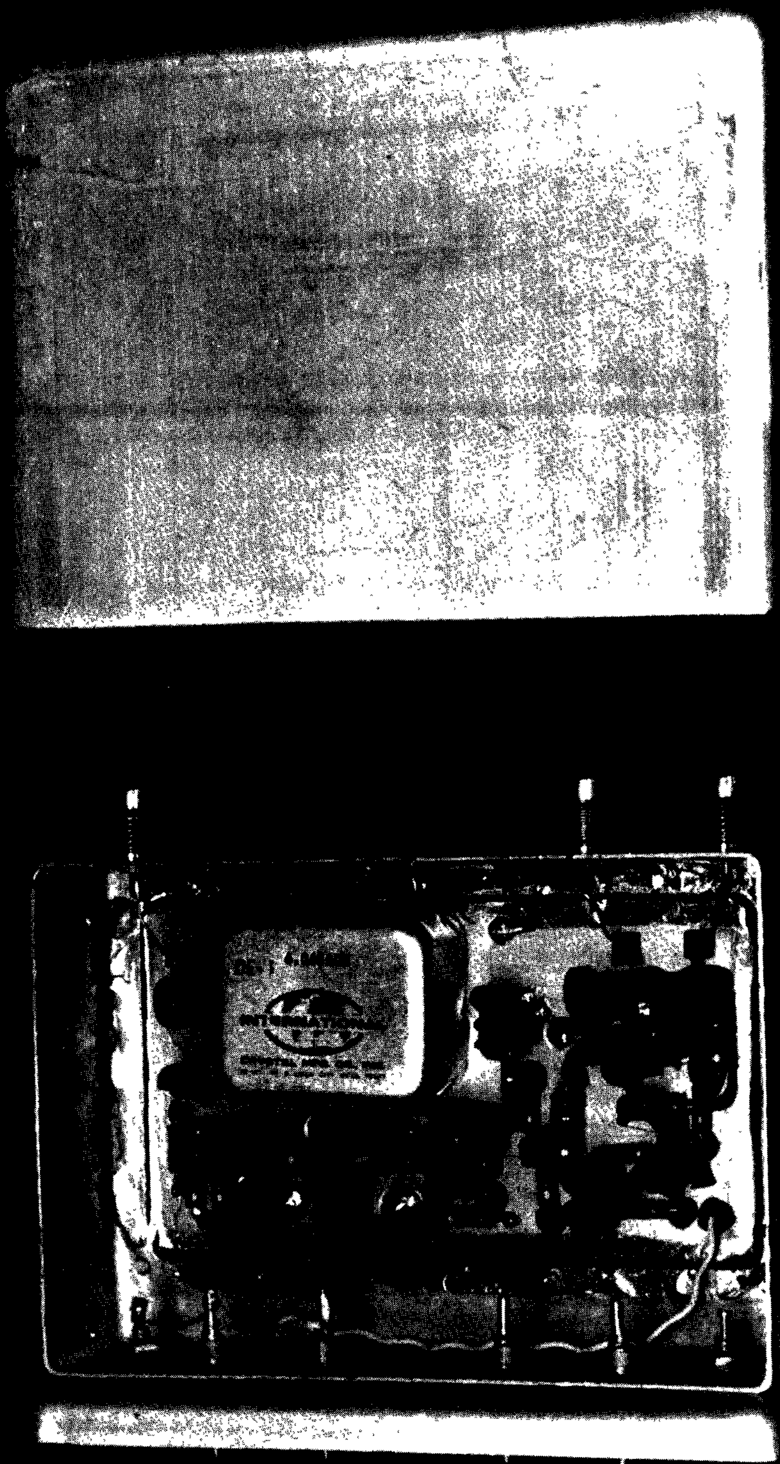


FIGURE 18. PHOTOGRAPH OF
RF MODULE

3. Data Acquisition Section

The design of the Data Acquisition Section was affected by requirements to minimize the possibility of introducing errors due to telephone line noise or heterodyne error, to accommodate receiver status information, to permit the addition of sensor information, and to allow the remote control of receiver functions.

To reduce the probability of introducing errors in the Doppler difference formulation, the accumulator is located at the receiver site. The accumulator runs continuously and is sampled to provide data. Instantaneous noise bursts on the telephone line can only introduce errors during a particular sample interval; the accumulator is unaffected. Second, the data are transmitted digitally; this provides some protection as certain transmission errors may be detected by monitoring character parity, etc. Third, command transmissions to the receiver sites are encoded with redundancy to minimize the probability of the receiver responding to a false transmission.

The selection of digital data transmission improves flexibility since the data message was readily expanded to include status bits, and space for sensor information could be included. The digital system also provides the medium for command transmissions. Such transmissions are encoded for reliability as discussed in the following text.

The basic data rate chosen was 1200 baud to provide reasonable resolution in the sampling process. Sampling time uncertainty of about $\pm$ .25ms is achieved.

Ideally the FD_o accumulators in all METRAC receivers would be simultaneously sampled. This condition is approximated by simultaneously transmitting sample commands to all receiver sites. No accumulative differential timing errors can occur. The sampling process is nonideal because of differential delays in the pulse transmission paths and uncertainties in pulse detection time due to infinite bandwidth and signal/noise ratio. Differential delay was measured to be less than 10ms while the uncertainty in detection time was minimized by using 1200 baud modems to transmit data.

The METRAC receiver data acquisition section performs two system functions:

1) Commands initiated by the command site are received and decoded to control receiver site circuitry, and
2) Receiver site data are accumulated, sampled, then transmitted to the command site.

The data acquisition section is capable of decoding four commands. Presently, three commands are used. Received commands zero the FD_o accumulator which generates the multiplied Doppler signal data, place the receiver AFC circuits in a sweep mode to acquire the reference, or sample the receiver data. A fourth command could control receiver power status, etc. The commands are demodulated by a modem to a serial data format, converted from serial to parallel using a UART module, and decoded in a command decoder. Redundancy is used to improve command transmission reliability.

Acquisition of data at each receiver site is initiated by loading a buffer register upon receipt of a sample command; the resultant receiver sample presently contains accumulated Doppler frequency information and digital status bits describing the condition of receiver circuitry and signals. Provision has been made to incorporate data from up to two sensors in the data message.

The buffer register contains four bits of receiver identification, seven digits of FD_o accumulator data, and eight bits of status information. The data are converted from parallel to serial using a UART, and transmitted by a modem connected to leased telephone lines. The serial data is received by the command site and processed to form a sequential record on a cassette data recorder.

The METRAC Data Acquisition Section logic at each receiver site consists of three logic cards and a modem; these appear in Figure 19. These logic cards are labeled with the following mnemonics:

RBD-1 --- ACCUM./REG.
RBD-2 --- UART/CMD-DEC.
RBD-3 --- RCVR Timing

- RBD-1

This card accumulates the multiplied, offset, frequency difference information and provides a buffer register for sampled receiver data. The FD_o signal pulses from the Analog Processing Section are counted in a seven decade BCD counter (FD_o accumulator). The accumulator contents and status flag bits are sampled by loading a buffer register upon receipt of a sample command. The buffer register data is transmitted in eight bit groups (characters). The lower order eight bits are loaded into the UART; after transmission, shift pulses load the next character in the lower order location. The sequence is repeated until eight characters (sixty-four bits) have been transmitted.

- RBD-2

This card contains the parallel/serial converter (UART) and a command decoder. Transfer of data from the buffer register to the modem is accomplished using a 'UART' chip; UART is the abbreviation for 'Universal Asynchronous Receiver-Transmitter'. The UART transmitter section converts parallel data into a serial word consisting of eight bits of data in addition to start, parity, and stop bits. Serial data from the UART is the modem SEND DATA input.

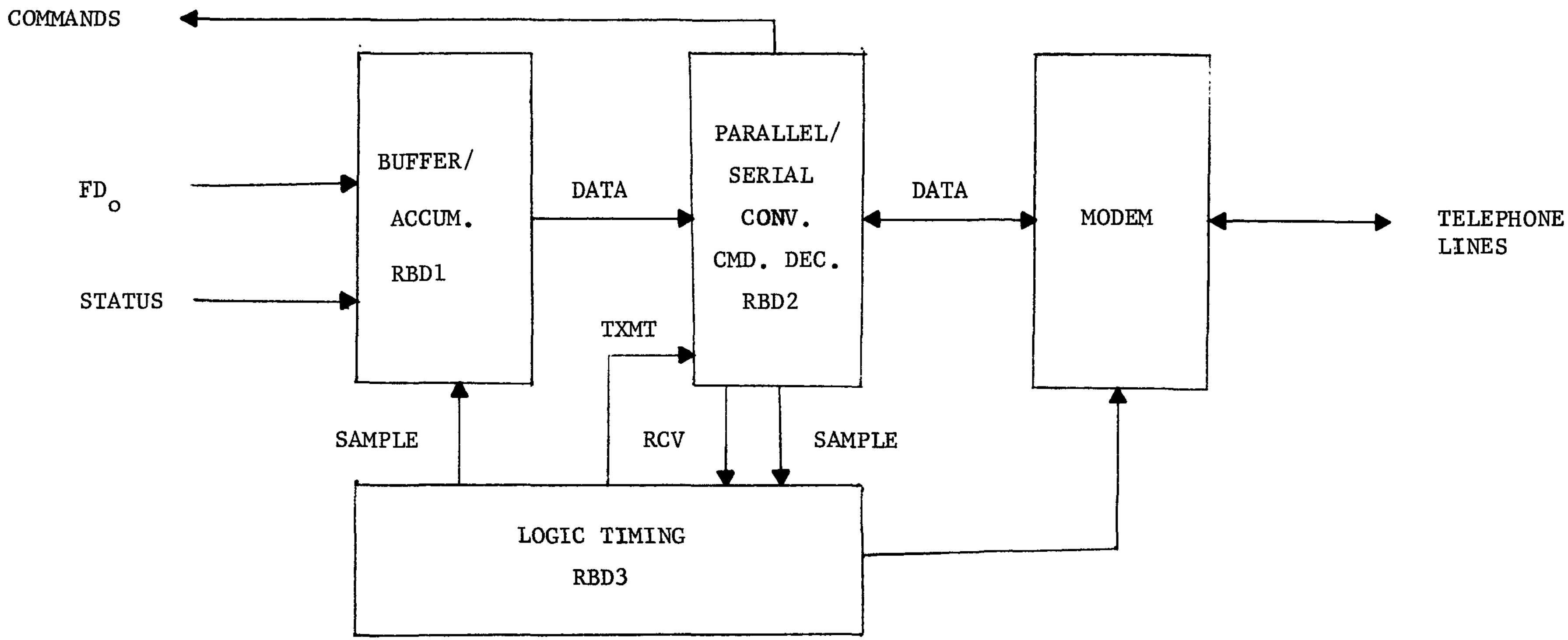


FIGURE 19: DATA ACQUISITION LOGIC
BLOCK DIAGRAM

The UART receiver section converts serial data from the modem RECEIVED DATA output into parallel data. Code transmission is verified by checking for data parity and receipt of a valid stop bit. One eight bit parallel word is produced for each character transmitted.

Command site transmissions are one character in length. The four possible commands are encoded with redundancy in that two identical four bit bytes are transmitted. The command decoder compares the received bytes at the UART receiver data output; a command output is produced only if the received bytes are identical and received data parity exists. These decoding requirements minimize the possibility of initiating a false command at the receiver site. The command decoder outputs source the 'Acquire Reference', 'Zero Accumulator', and 'Sample' pulses required by the receiver site.

- RBD-3

This receiver board generates the timing and control signals required by the Data Acquisition Section. Timing signals required for modem operation are derived from a crystal oscillator.

- Modem

Data is exchanged with the command site using modems operating over leased telephone lines; either two wire or four wire lines can be used by the proper modem connections. The data rate used is 1200 baud, which provides the resolution required for the sample command and also permits future expansion of the data message to include data from several receivers. The modems encode serial data for transmission and decode received signals to serial data.

D. Receiver Checkout Unit

A receiver checkout unit was designed to facilitate the checkout and maintenance of the METRAC receiver. The unit is connected to the METRAC receiver by a multi-conductor cable such that the contents of a receiver sample are displayed. Receiver FD_o accumulator contents, station ID, and receiver FD_o, as well as receiver status bits, are presently displayed. Provision has been made to incorporate displays for sensor data.

A photograph of the receiver checkout unit appears as Figure 20. The different displays provided are located as follows. The top row provides seven digits of display of FD_o accumulator contents, while the second row contains one hexadecimal display for station ID. This row also contains a provision for two three-digit groups of sensor data. The bottom row of display indicates FD_o, the rate of change of the FD_o accumulator data. Two columns of four light emitting diodes provide display of the receiver status bits. All displayed data are loaded on receipt of a sample pulse from the receiver.

A block diagram of the checkout unit appears as Figure 21. Two circuit cards are required. The card labeled MBD1 contains the display devices, while MBD2 contains circuitry to load the receiver sample into the proper display, to control the FD_o display, and to alternate display blanking (included to reduce power requirements). The circuit cards and a power supply are mounted in an instrument case. The unit operates with 117 volt AC power.

E. Command Site Console

The command site console controls the operation of the METRAC receiver site equipment. The receiver network data (receiver samples) are sampled, then buffered and formatted to produce a sample record which is recorded on a cassette

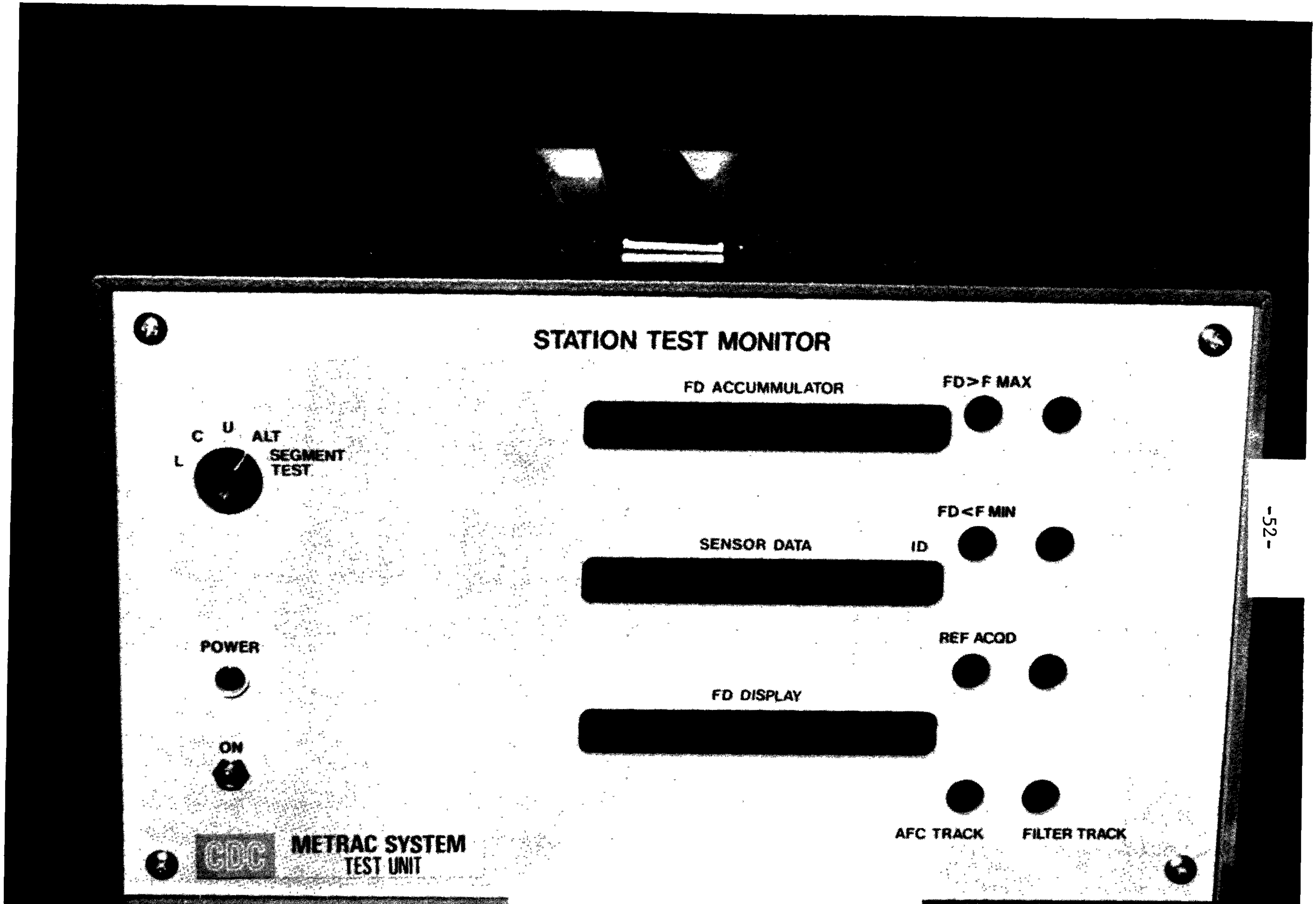


FIGURE 20. PHOTOGRAPH OF RECEIVER CHECK-OUT UNIT, FRONT

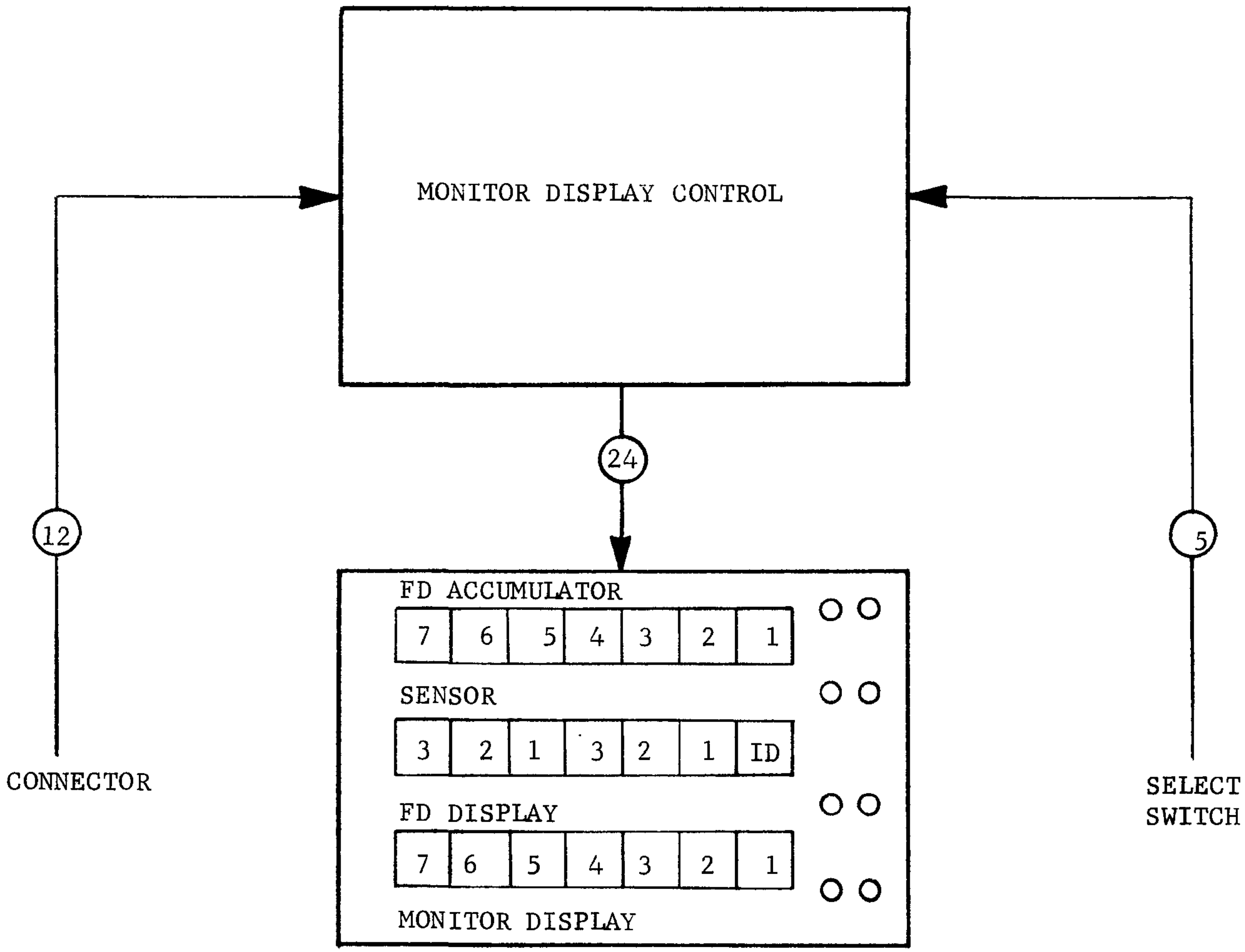


FIGURE 21. BLOCK DIAGRAM - METRAC RECEIVER CHECK OUT UNIT

tape data recorder. A data monitor function provides command console display of selected receiver site data. The command console also contains a reference transmitter control unit which provides remote control of the reference transmitter site equipment. Figure 22 shows a block diagram of the equipment present at the command site.

The command site initiates both manual and automatic commands for receiver control by generating four independent commands. The first (and automatic) command is the sample command. Pulses generated by a sample pulse generator initiate the transmission of a sample command to all receiver sites. The transmission time is concurrent for all channels. In response to this command receiver sites will sample their data and automatically transmit this data to the command site.

Three manual commands may be programmed on the command console panel. A selected manual command may be transmitted to a selected receiver site or to all receiver sites. To minimize the possibility of accidental command transmission, a step sequence must be completed to send a command. First, the command is selected with a two position toggle switch, after which a station select push button is depressed. The command transmission occurs upon depression of a "Send Command" push-button switch.

The three manual commands are "Zero accumulator", "acquire reference", and at present, a spare. The zero accumulator command sets the FD_o accumulator at selected receiver sites to a count of zero which facilitates the determination of proper receiver operation previous to balloon release and provides a starting point for position computation.

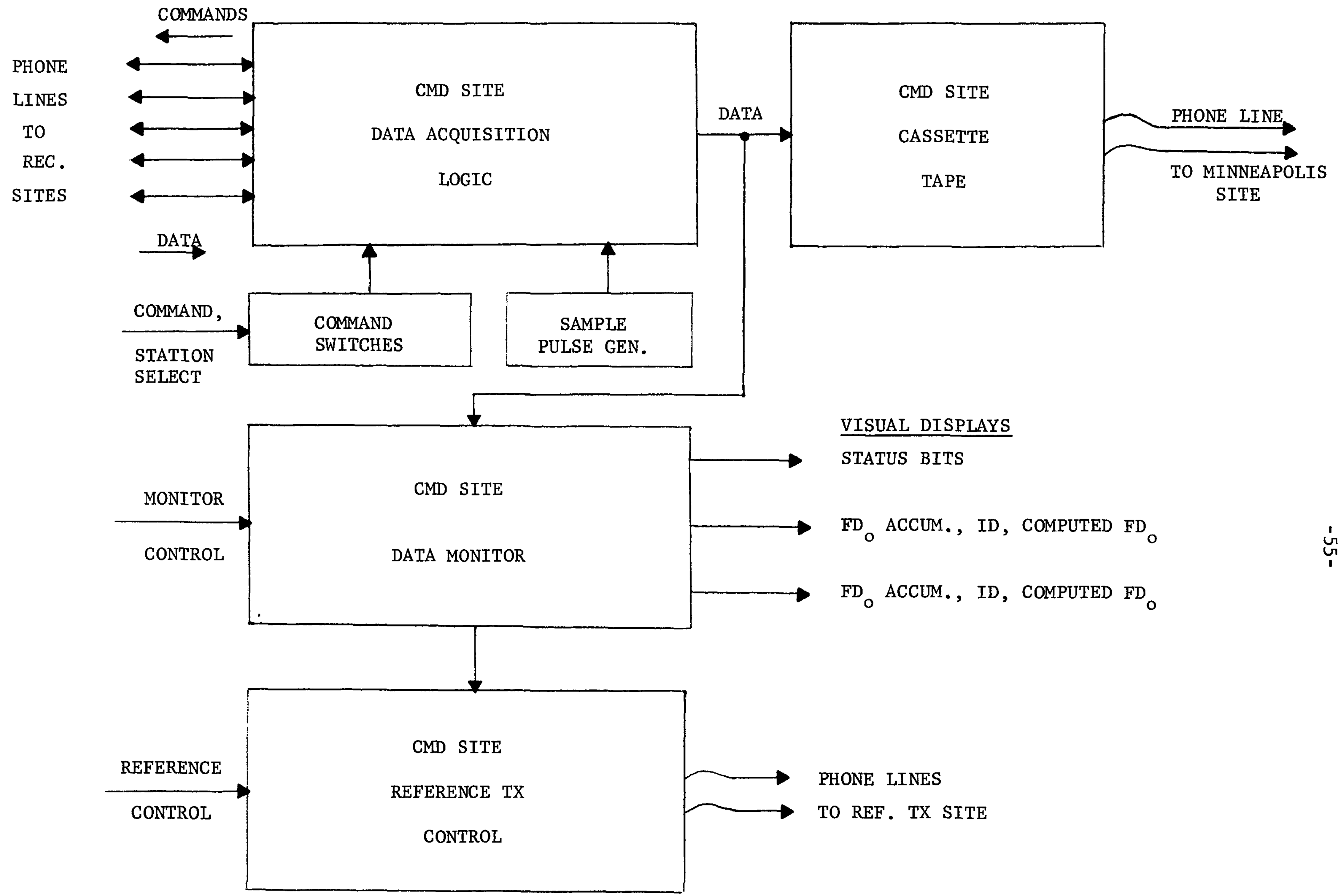


FIGURE 22: BLOCK DIAGRAM COMMAND SITE EQUIPMENT

The "acquire reference" command enables the search by receivers for the reference signal. The presently unused spare command could be utilized in a future system to control receiver power, etc.

Acquisition of data from receiver sites is initiated by the transmission of a sample command. Receivers decoding this command will sample this data, buffer it, and transmit it to the command site. Modems at the command site translate this data into a serial stream. The serial asynchronous data are reformatted into eight bit parallel words and stored in buffer registers. After all receivers have responded, the data stored in the buffers is read out sequentially and recorded by a cassette tape unit. One sample record of data from all receivers is recorded for each sample pulse issued by the command site.

A sample pulse generator supplies the command site timing pulse which generates the sample commands; the time interval between sample pulses is internally programmable by means of a card mounted switch. The interval may be varied in one second increments from a minimum of one second to a maximum of fifteen seconds. This could permit a reduction in the amount of data generated during a balloon flight. The selected time interval is produced by digitally dividing the output of a crystal oscillator, which eliminates significant trajectory error because time uncertainty is maintained less than $\pm$ .01%.

The command site data monitor performs several system functions. First, this function aids in the checkout and maintenance of a large segment of the METRAC system as receiver and data acquisition equipment performance can be monitored and the receiver sample for any receiver site may be displayed. In addition, the data monitor provides reference transmitter frequency control information during a balloon flight. A display of FD_o, the rate of change of the FD_o accumulator, indicates what reference transmitter frequency change is required to maintain a nominal frequency difference. Finally, receiver site performance during a flight may be monitored by means of a continuous display of the status bits for all system receiver sites. Additionally, the difference in FD_o accumulator between two receiver sites may be displayed, which permits determination of proper operation at all receivers at launch.

The reference transmitter control unit permits an operator at the command site to turn transmitter carrier on or off for a balloon flight, testing, etc. The unit also enables tuning the reference transmitter frequency to maintain the nominal difference required for system operation. Information for frequency tuning may be obtained by observing the FD_o rate associated with any receiver site. The unit was designed to permit flexibility in that automatic and manual frequency control is provided. The automatic system contains limited safeguards to enhance operating reliability.

The command site console was designed mechanically to provide complete access to the electronic hardware and interconnect. The logic circuitry associated with command site data acquisition and the data monitor functions is mounted on a swing out logic chassis and logic cards are plugged into connectors mounted in this chassis. The various displays are mounted on the front panel which also swings out for access to the circuitry. Three photographs illustrate the construction used.

A photograph of the command site console front panel (Figure 23) shows most of the display units and control switches. The station data monitor contains the dual three row displays in the upper section of the front panel. Switches to control these displays are located directly below the displays. The status monitor display is located below the station data monitor display. The command select switches are at the left side of the panel, while station select switches are located across the front panel below the status display. The reference transmitter control unit was not installed at the time the photograph was taken.

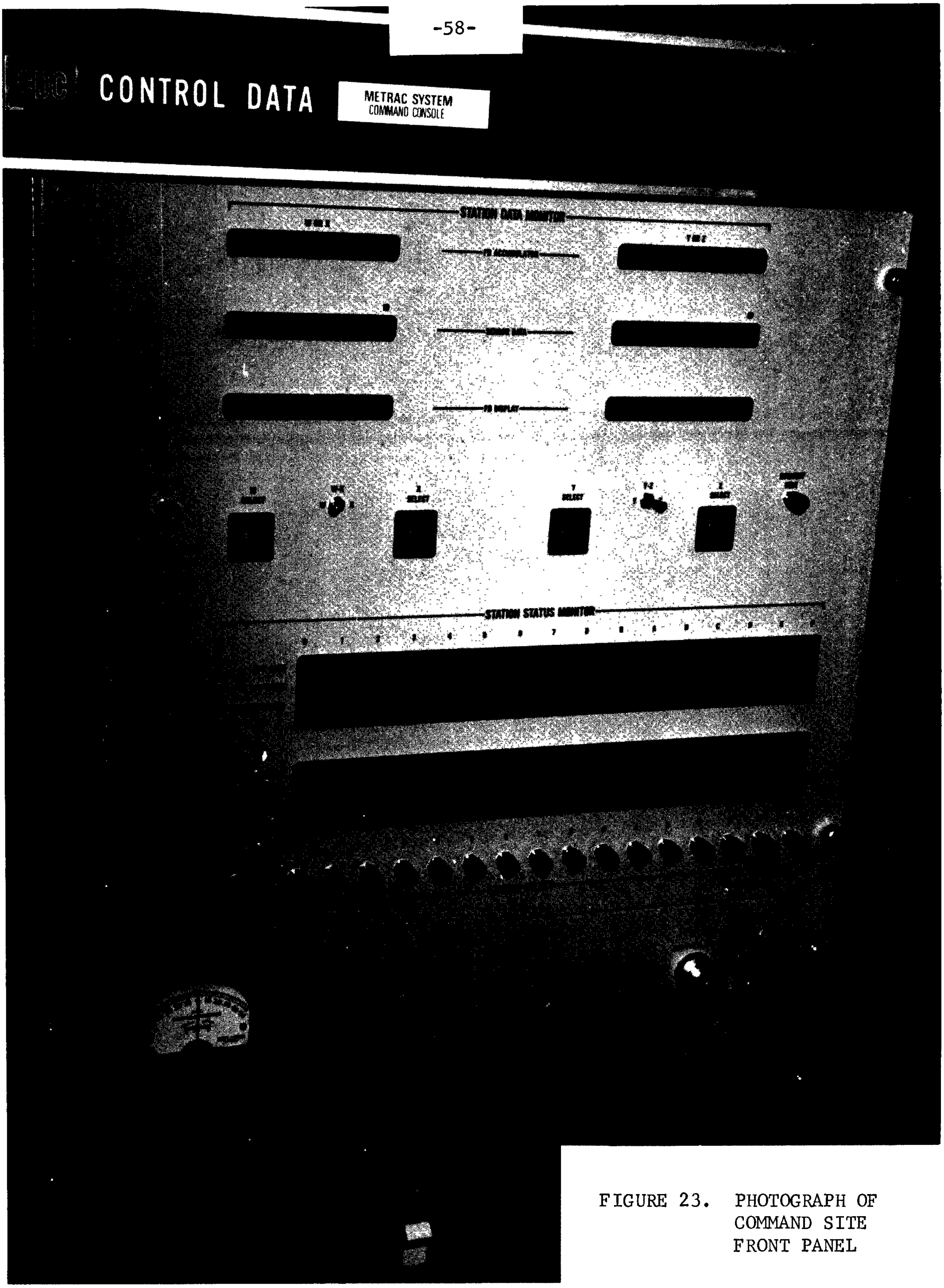


FIGURE 23. PHOTOGRAPH OF COMMAND SITE FRONT PANEL

Figure 24 shows the construction of the front panel. The station data monitor displays are located on two printed circuit cards, while the status monitor display is located on a third printed circuit card. Flexible woven cable is used to interconnect with the logic circuitry.

The rear view (Figure 25) shows the logic rack in an open position. The logic circuitry swings open for checkout and maintenance. Modems are mounted below this rack and the telephone line connections are made on the panel at the lower left of the view. The connector for data output to the cassette tape is at the top of the cabinet.

1. Data Acquisition Logic

The command site data acquisition logic accepts receiver network command inputs from command console switches and the sample pulse generator for the transmission to the receiver sites. To enhance transmission reliability, the commands are encoded and transmitted to the receiver sites. Commands are encoded as two identical four bit bytes and the resultant eight bit word is converted by a UART from parallel to serial form. The serial character which includes data, start, parity, and stop bits is the input to a modem which modulates a carrier to transmit data over leased telephone lines to the receiver sites.

Receiver sites decoding the transmitted sample command transmit their data message (receiver sample) to the command site and modems demodulate these transmissions forming a serial data stream. A UART performs a serial to parallel conversion. The data are stored in a buffer register, sixty-four bits (8 characters) in each channel buffer.

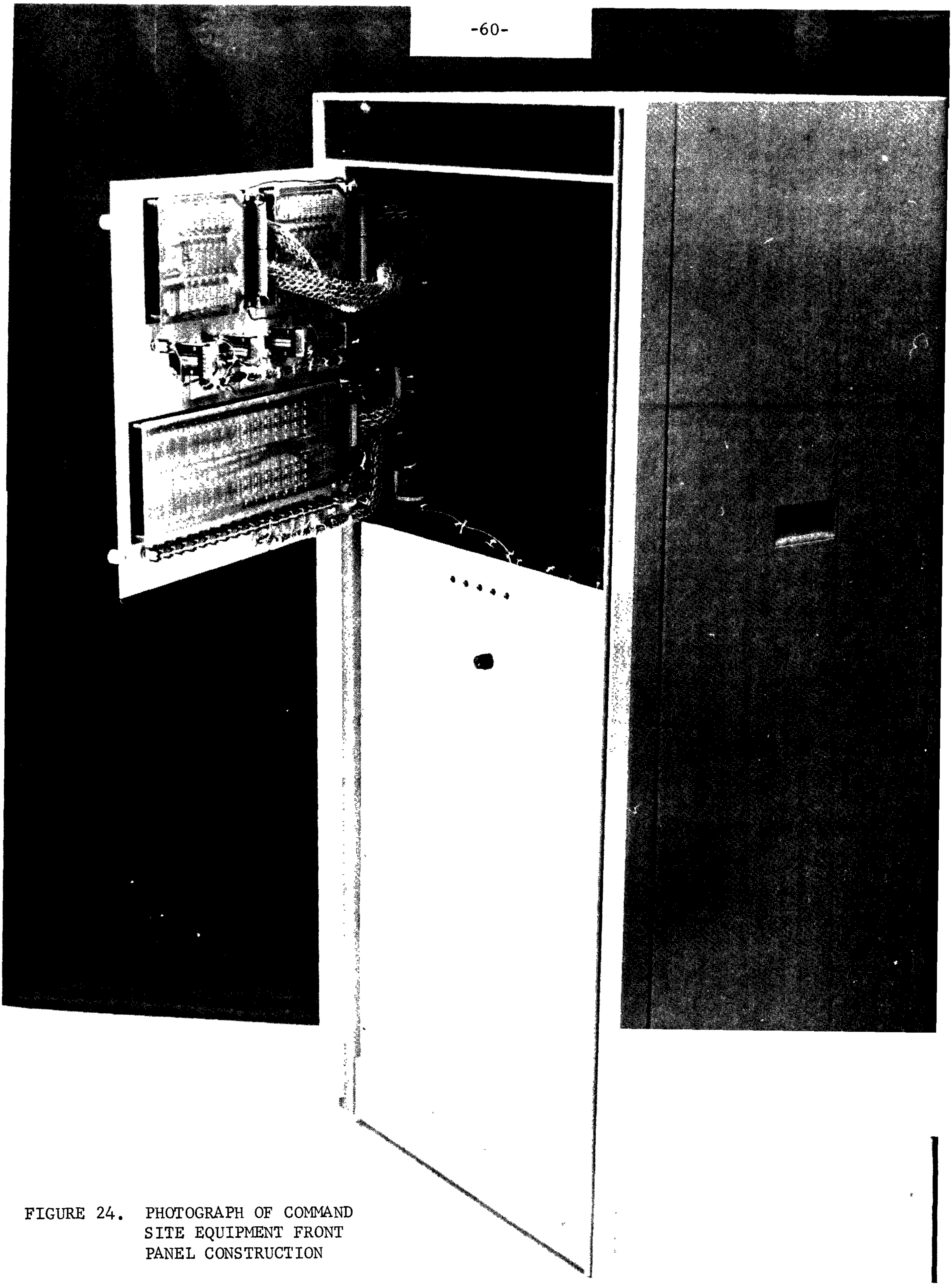


FIGURE 24. PHOTOGRAPH OF COMMAND SITE EQUIPMENT FRONT PANEL CONSTRUCTION

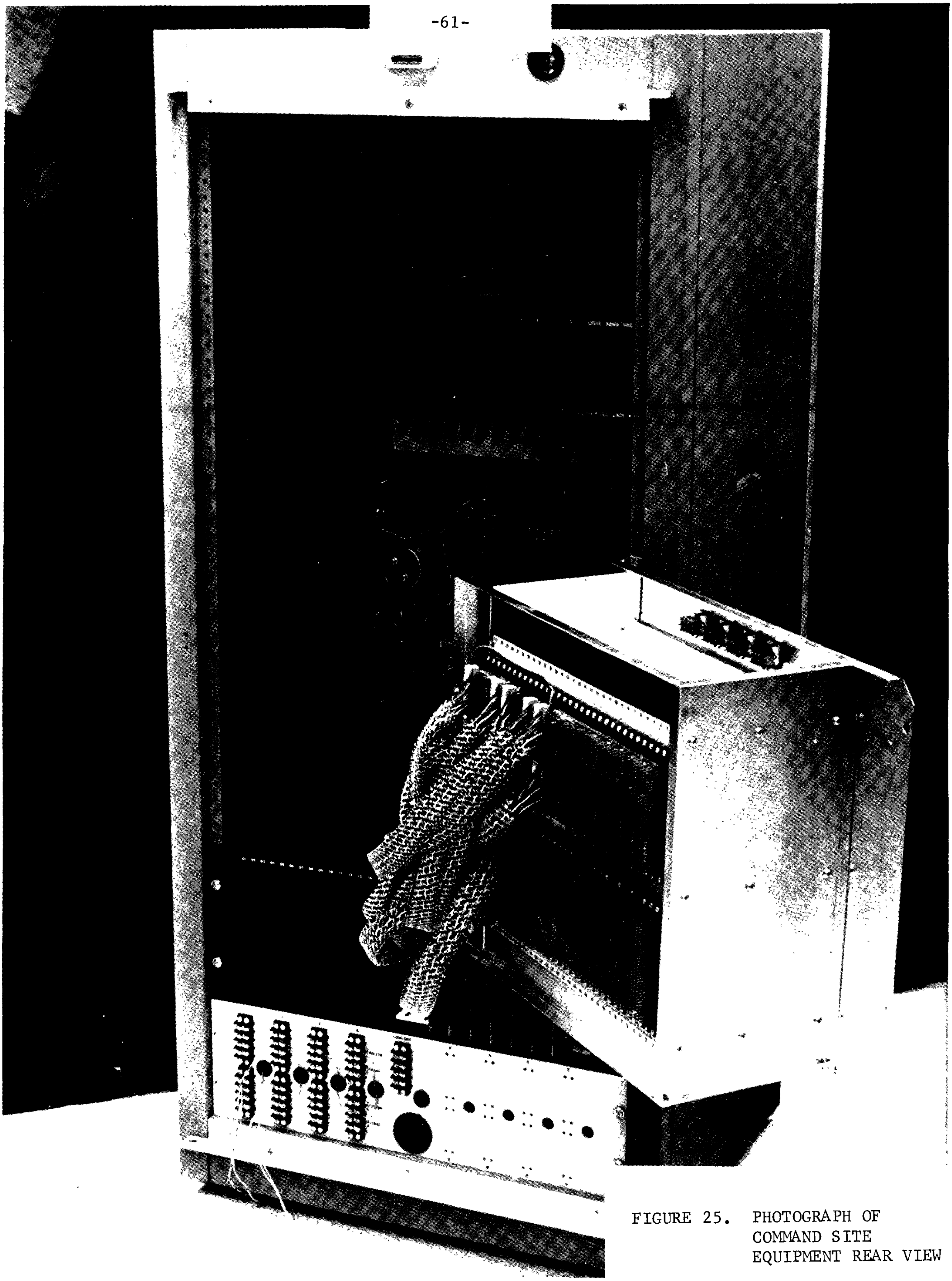


FIGURE 25. PHOTOGRAPH OF COMMAND SITE EQUIPMENT REAR VIEW

With data stored in the command site buffers, the recording process can begin. The outputs of the buffers are connected to a bus which is the data input to the cassette tape recorder. The buffers are enabled in sequence to form a sequential tape record. The buffer for Receiver #1 is enabled first and the cassette unit incrementally records the eight (8 bit) characters contained in the buffer. The process continues until data contained in each buffer has been recorded on the cassette tape. A sync word, consisting of eight bits of data (all logic ones), is written after the last buffer data entry to indicate the end of a sample record. The cassette unit now waits until the next receiver sample is returned and the data transferred signal is given. A new sample record is written by writing the contents of each buffer. Upon termination of a flight record, the tape is formatted into a 6600 compatible tape for processing.

Figure 26 shows the block diagram of the command site data acquisition logic. Each receiver site in the network requires three circuit cards, consisting of a modem, a modem interface card, and a register card. Two timing and control cards generate the control signals required by the data acquisition logic section.

The modem interface card provides the interface required between the modem and data acquisition logic and also contains the logic to produce the command signal transmitted to receiver sites. The card contains the serial to parallel converter indicated on the block diagram. A UART (Universal Asynchronous Transmitter Receiver) converts the eight bit parallel data format used within the data acquisition logic to/from the asynchronous serial data format at the modem. Commands generated by the sample pulse-generator or command console switches are encoded in the command encoder logic, producing an eight bit character for transmission. The command is converted to a serial format and transmitted by the modem upon receipt of a pulse from the sample pulse generator.

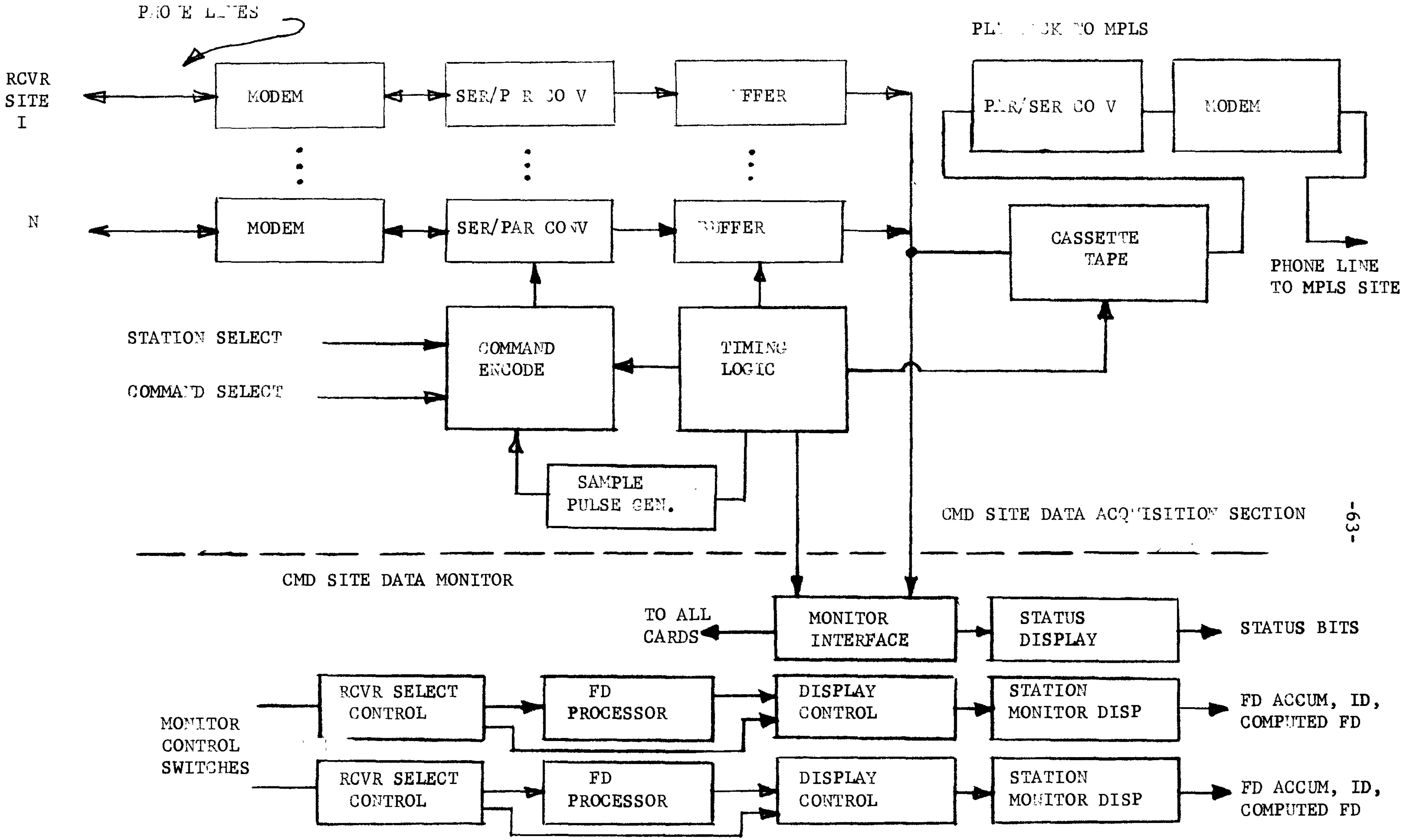


FIGURE [illegible]. BLOCK DIAGRAM COMMAND SITE DATA ACQUISITION LOGIC

When receiving data from the receiver sites, the modem data output is converted from serial to parallel by the UART. The modem interface card controls the loading of this data into the register card. The eight parallel UART data output lines are the inputs to the register card, such that the register is loaded with eight bits (one character) each time the UART indicates a data character is ready (DR pulse). A character counter is advanced by the data ready pulses; when eight characters have been counted, the transition to a count of eight fires a one shot to generate a 'Data Received #1' pulse. The command site control logic uses this pulse to determine when data is buffered and ready for sequential output. Control signals enable the transfer of data from the buffer and data is shifted out sequentially by character.

The register card contains the 64-bit buffer which stores the received sample from the receiver sites. The buffer is constructed as a shift register eight stages in length with eight bits of parallel storage per stage. The buffer input is eight bit parallel data from the UART, while the buffer output is to the bus providing eight bit parallel data to the tape unit and command site data monitor. Control signals from the monitor interface card control the register.

The bus logic card (one of the two timing and control cards) controls the readout of data from the buffer registers and also supplies timing pulses required for UART operation. 'Data Received #I' pulses from all monitor interface cards are wire or'd together. The first such pulse sets the tape unit in a write mode and clears a counter (Receiver Enable Counter). Data from receiver #1 is read out of the buffer and written on tape. The counter is then advanced and data from receiver #2 is written. The process continues until data from all receivers is written on tape.

• Cassette Tapes

The cassette recorders used in METRAC are incremental digital cassette storage and retrieval systems which record and playback eight bit characters. When writing, the recorder accepts a parallel eight bit character and a start signal at TTL logic levels. When reading, each start signal will cause one eight bit character to be read and presented in parallel at the output, together with a strobe signal. Outputs are TTL levels.

Data is recorded on standard Phillips certified tape cassettes in complementary NRZI format. The recorder operates incrementally at rates up to 120 characters per second when recording and up to 100 characters per second when reading. When read continuously, as is done in METRAC, the output data rate is approximately 110 cps.

When writing, the first character on tape is C1 (Character 1) of receiver #1. Then the remaining characters of receiver #1 are written, followed by the characters of receiver #2, and so on. After a complete Sample Record is written, consisting of 56 characters (8 Char/receiver x 7 receivers), a sync word is written consisting of all ones. This gives a total of 57 (8-bit) characters per Sample Record.

2. Data Monitor

The command site data monitor, located within the command console, contains three display units. The status monitor display continuously indicates the condition of the eight status bits associated with each receiver site for up to 16 sites.

Two identical and independent station data monitors each provide display of a receiver sample (FD_o accumulator, ID, provision for sensor data) and FD_o, the difference between FD_o accumulator samples. Each monitor contains two one-of-sixteen station select switches which are labeled W and X, Y and Z. A third switch enables display of the receiver sample for: 1) Station Select W (or Y); 2) Station Select X (or Z); and 3) Display Alternates between W and X (Y and Z). The FD_o display for 1) and 2) indicates FD_o, the change in FD_o accumulator between two consecutive samples and in 3), the FD_o display indicates the difference in FD_o accumulator data between station W and station X or station Y and station Z.

The command site data monitor block diagram appears in Figure 27. Here signals from the Data Acquisition Section (data bus and timing) pass through the monitor interface to the data monitor cards. The status display card latches the eight bits of status information in each receiver sample and light emitting diodes provide the visual display.

Each station data monitor contains four cards. The station monitor display card contains an upper row of seven latching BCD readouts for FD_o accumulator data, a center row with a latching hexadecimal ID display and space for two groups of three latching BCD readouts for sensor data, and a lower row of seven counter/latch BCD readouts for FD_o displays. The receiver select control card compares station select switches with timing pulses; a pulse, MR, enables the display control card to load the receiver sample into the monitor display card. The receiver select card also controls the operation of the FD processor card. FD_o accumulator data are loaded and the difference (FD_o) is computed and displayed by the monitor display card.

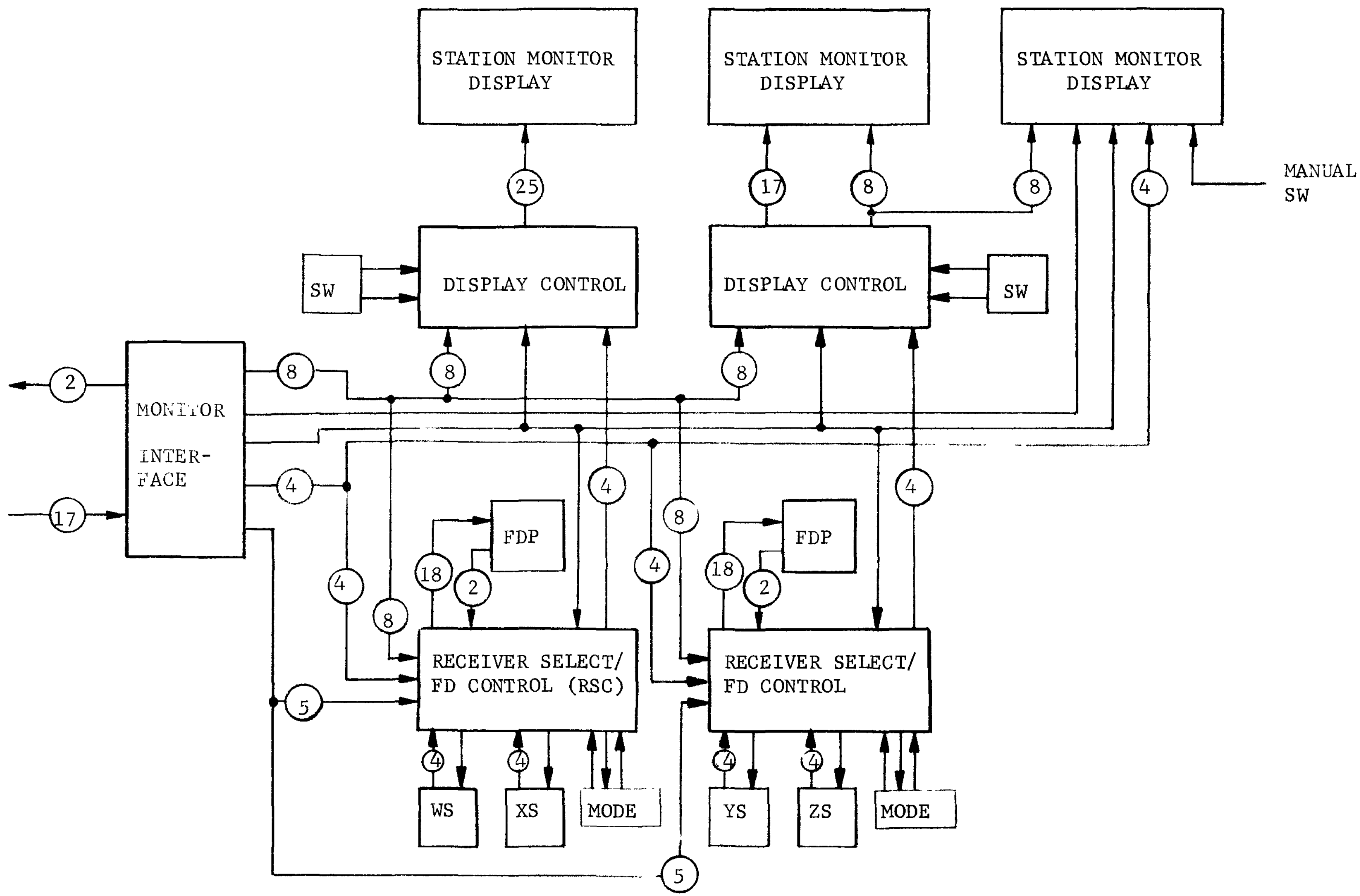


FIGURE 27. COMMAND SITE DATA MONITOR BLOCK DIAGRAM

3. Reference Transmitter Control

The reference transmitter control unit is housed within the command site console to provide carrier on/off and frequency control. The carrier is turned on or off with a front panel switch and indicator lights show the carrier condition. The reference transmitter frequency may be controlled manually or automatically. In the manual mode of operation the operator observes the FD_o display for a selected station and adjusts a ten-turn potentiometer to maintain a nominal frequency offset. In the automatic mode, an AFC loop is formed by the reference transmitter, a selected receiver site, and the command console. The operator selects the receiver site to be used for frequency control by operating the station select switches in the W(X) station data monitor; a primary site and back-up site are selected.

A front panel tuning meter indicates the difference in control voltage between the manual control potentiometer and the AFC circuitry. The operator nulls this meter so that a changeover to manual control can be made without disrupting system operation. Mode of operation is selected by a front panel switch and L.E.D.'s indicate the mode in use. Operation will transfer to the manual mode if five seconds elapse with FD_o outside the range of 2 to 8 KHz.

Figure 28 shows the hardware to realize the control function consisting of the mentioned controls, indicators and meters, a frequency control card, and a remote control unit. The frequency control card accepts inputs for frequency control from the manual control pot and from the FD_o display of the W(X) station data monitor. The AFC path uses a D/A converter and error amplifier to provide the frequency control voltage to the remote control unit. The frequency control voltage from the control card and the carrier control commands are encoded for voice grade telephone line transmission to the reference transmitter site using components manufactured by CDC Autocon. The control voltage is the input to a

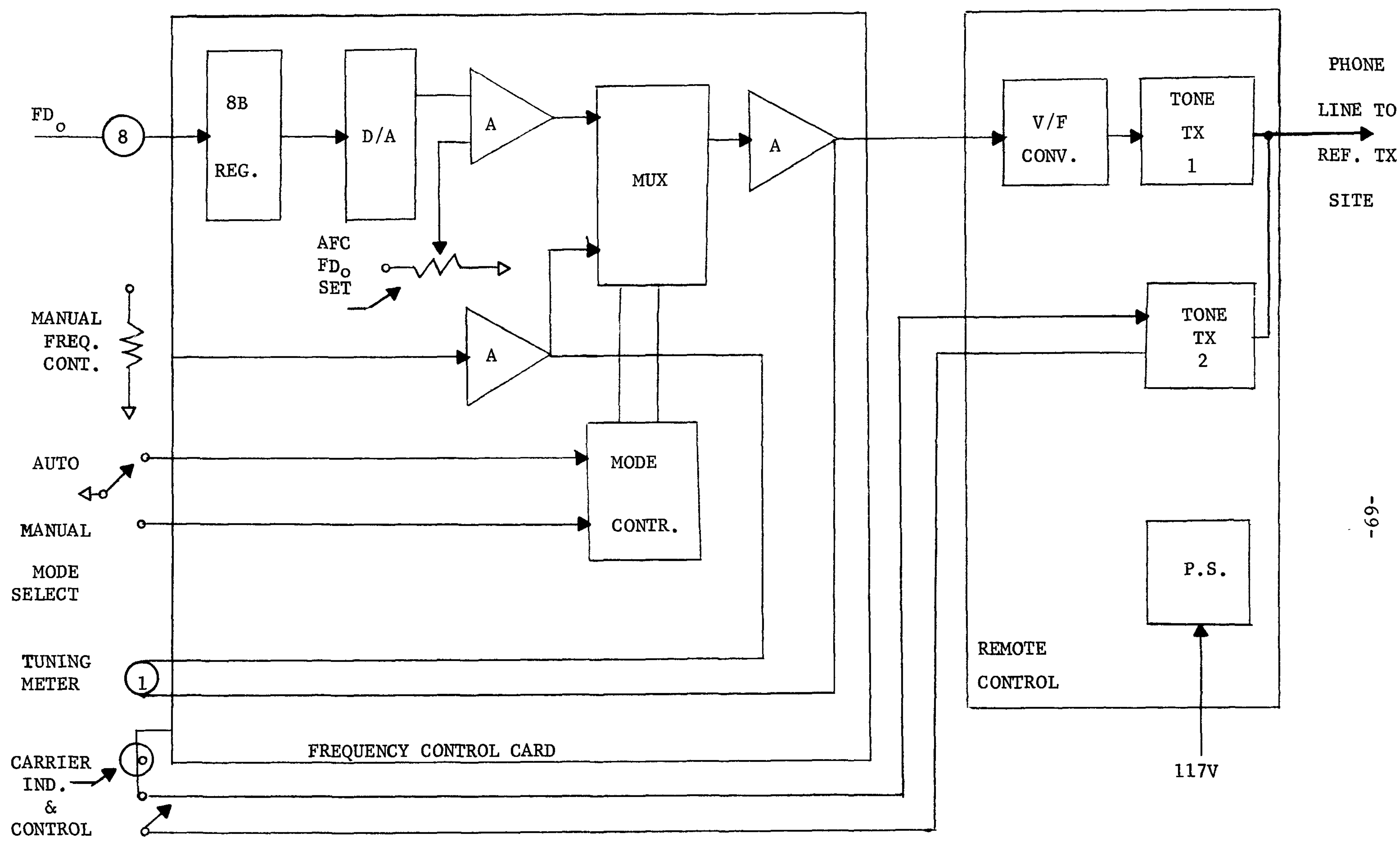


FIGURE 28: BLOCK DIAGRAM CMD SITE REFERENCE TRANSMITTER CONTROL

voltage to frequency converter such that the varying frequency output keys a narrow-band FSK tone channel transmitter. The transmitter outputs are combined and connected to the telephone line.

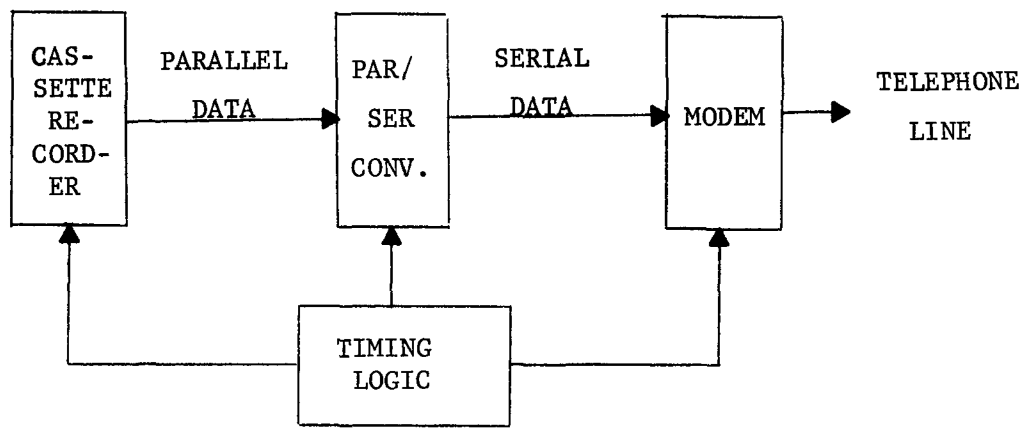
F. Minneapolis Site

The Minneapolis site is the final stage in the process to convert receiver site data to a computer compatible format. Data produced by the command site and written on magnetic tape cassettes is translated into CDC 6600 compatible tapes.

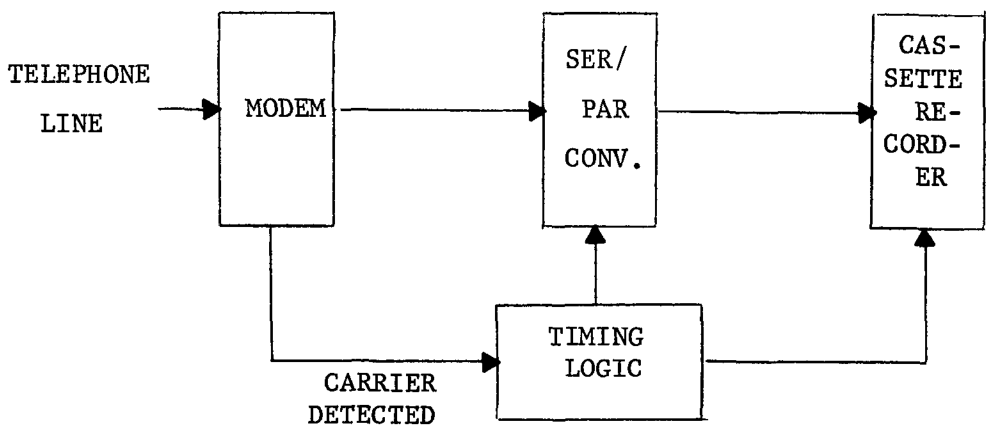
In order to expedite the conversion process, a data retrieval link capability is included in the Minneapolis site equipment. The cassette data recorder at the command site, a telephone line, and the Minneapolis site equipment allow the duplication of the command site tape.

Figure 29 shows the block diagram of the data link. At the command site a completed cassette is loaded and read by the cassette recording unit. This data is in an eight bit parallel format, with a UART used to produce a serial data format. A 1200 baud modem then encodes the data for transmission. Data into the Minneapolis site is demodulated by an identical modem, formatted by a UART into parallel data, and recorded on another cassette tape unit. The data is transferred between tapes at 1200 baud.

Tape cassettes produced by the command site and transferred to the Minneapolis site either by the data link or by physically transporting the cassette are then reformatted. Figure 30 illustrates the functions in the process. The eight bit characters on the cassette are converted into six bit words for 6600 use. The data are reformatted by reading three 8 bit characters from the cassette into a 24-bit buffer. The data are then read out as four 6-bit words and written on a Kennedy 1708 tape unit, producing the desired tape.



DATA LINK FROM COMMAND SITE TO PHONE LINE



PHONE LINE TO MINNEAPOLIS SITE DATA LINK

FIGURE 29: BLOCK DIAGRAM DATA LINK

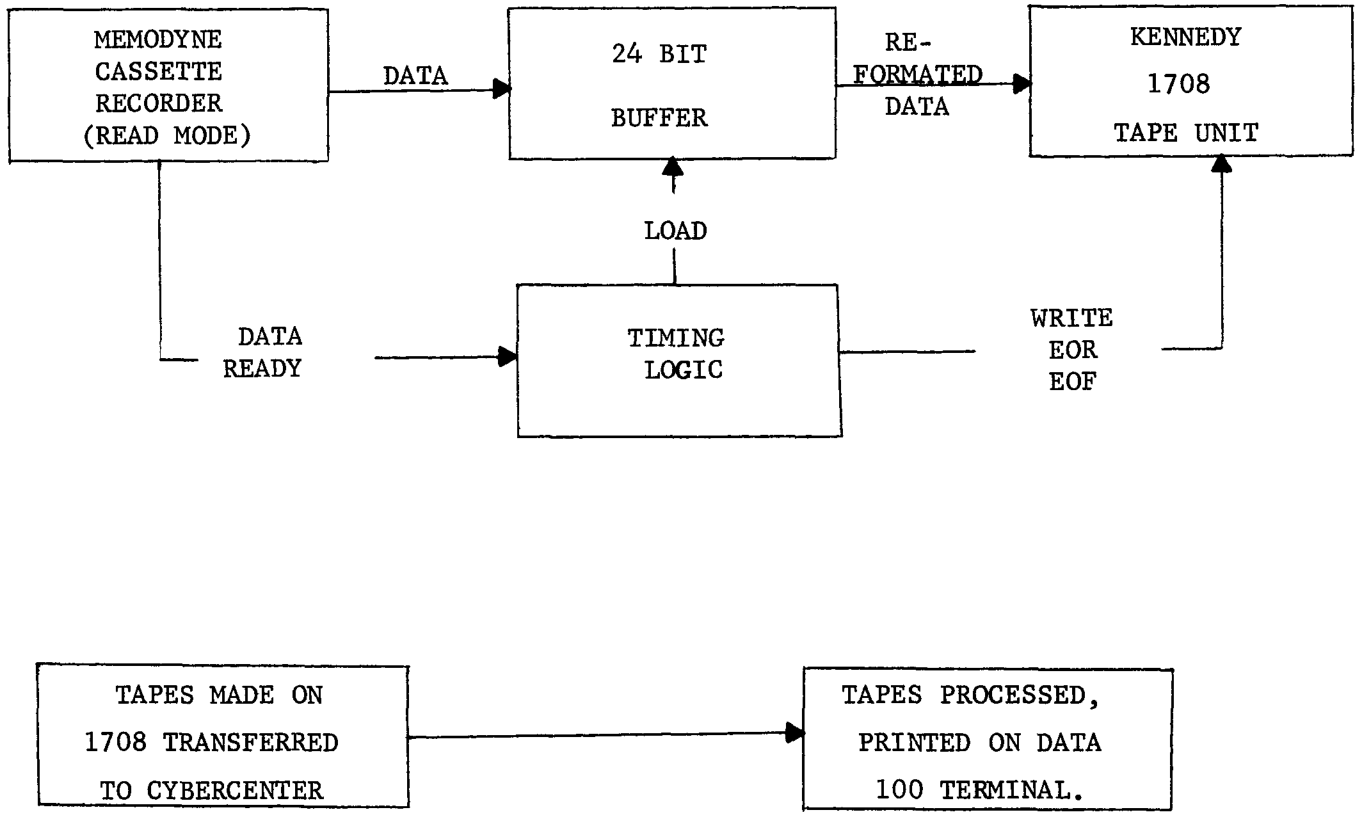


FIGURE 30: 6600 TAPE GENERATION AND PROCESSING

As the data is read from the cassette, the buffer input looks for a valid sync word consisting of all ones (one character of all logic ones). The first sync detected will enable the timing circuit to gate in the first three characters (after sync) to the buffer. The six parallel bit words are clocked out sequentially at a 4.8 KHz rate and recorded on the Kennedy 1708 tape transport; this rate enables the cassette recorder to read continuously to minimize tape production time.

Reading of the cassette and recording by the Kennedy transport continues until all data is transferred to the Kennedy. Sensing that data is no longer coming from tape, the interface enables an end of file to be written on the tape. The tape made on the Kennedy is then ready for processing by a 6600 computer.

VI. METRAC™ POSITION DETERMINATION

A. Discussion of the Problem

The problem of computing the location of a balloon borne transmitter by measuring accumulated differential doppler frequency between pairs of fixed land based receiver stations reduces very naturally to a problem of solving a set of hyperbolic equations. This type of solution is common in such navigational techniques as LORAN and OMEGA.

To describe the METRAC principle, consider the two dimensional example depicted in Figure 31. This figure shows a sample set of hyperbolas formed with two receivers serving as the foci. As a transmitter is moved from Point A to Point B, receiver 2 accumulates a frequency count larger than the transmitted number of cycles while receiver 1 accumulates a smaller count. If the transmitter were to move along one of the hyperbolas, both receivers 1 and 2 will count the exact

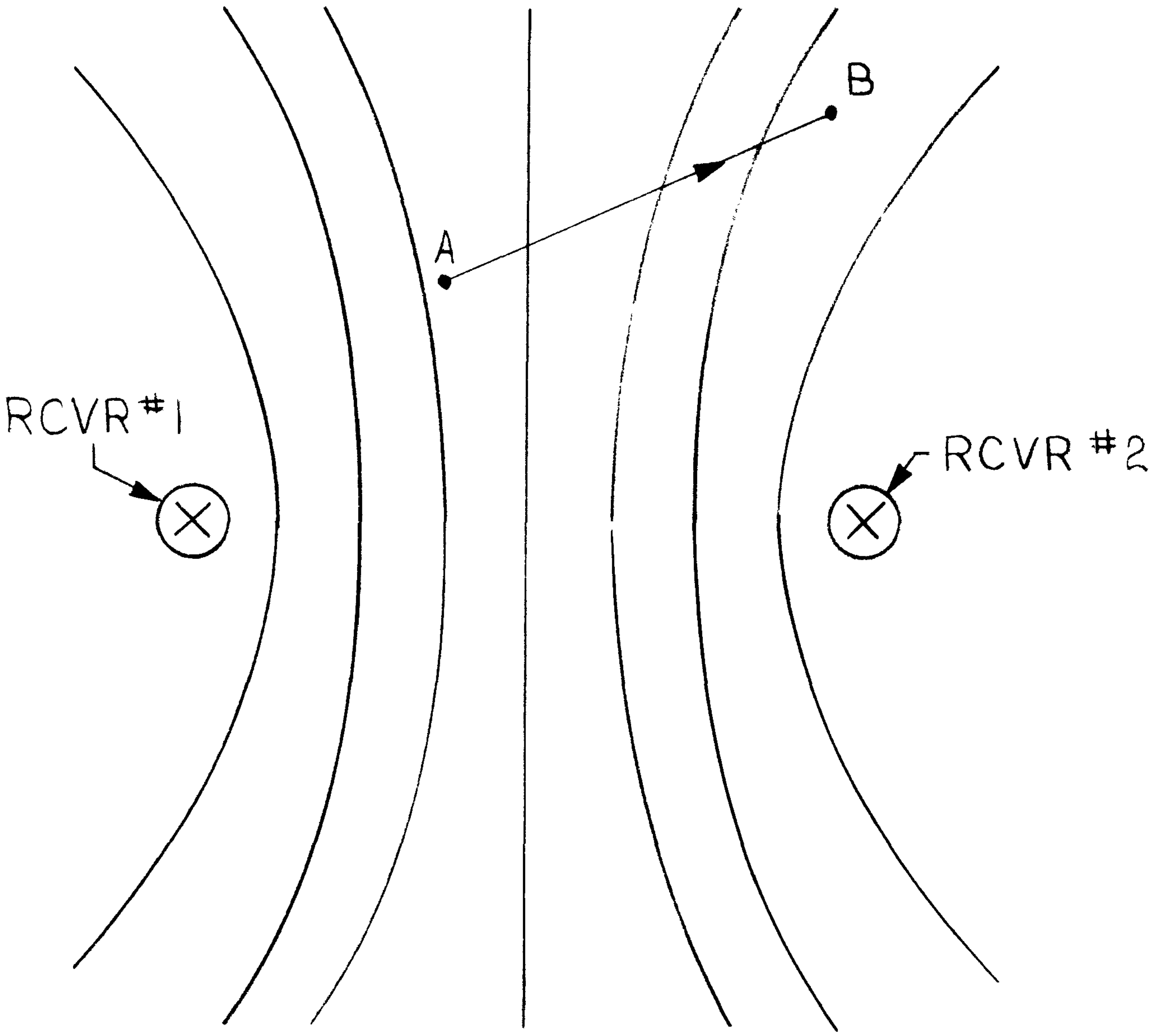


FIGURE 31. Hyperbolas Formed By Two Receivers

number of cycles transmitted. The difference in the number of cycles counted between two receivers such as 1 and 2 is called the differential doppler and is equal to twice the number of hyperbolas crossed by the transmitter.

Since the number of cycles counted at the receivers is an integer number, there are exactly dM/λ hyperbolas defined by two receivers separated by a distance d and a transmitter operating at a wavelength λ and a frequency multiplication factor of M. The separation of the hyperbolas on the axis joining the two receivers is λ/M. For a frequency of 403 MHz and a multiplication factor of 8 as was utilized in this work, the separation is about 10 cm. This corresponds to the finest position resolution possible for the given frequency and multiplication factor.

The differential doppler accumulated over a fixed time interval is independent of the path taken. In addition, there are a doubly infinite number of possible starting and stopping positions A and B which yield the same differential doppler. By knowing the starting point and obtaining two independent measures of the differential doppler (i.e., by using three receiver stations), one can compute the final position in terms of the intersection of appropriate sets of hyperbolas as is shown in Figure 32.

For practical balloon tracking, we clearly need to be able to specify a three dimensional position. The preceding discussions easily extend to three dimensions for which case the hyperbolas become hyperbolas of revolution.

Four stations are then required to define three measurements of differential doppler from which the solution can be derived. Mathematically, there are two valid solutions to this problem. One, however, is generally underground.

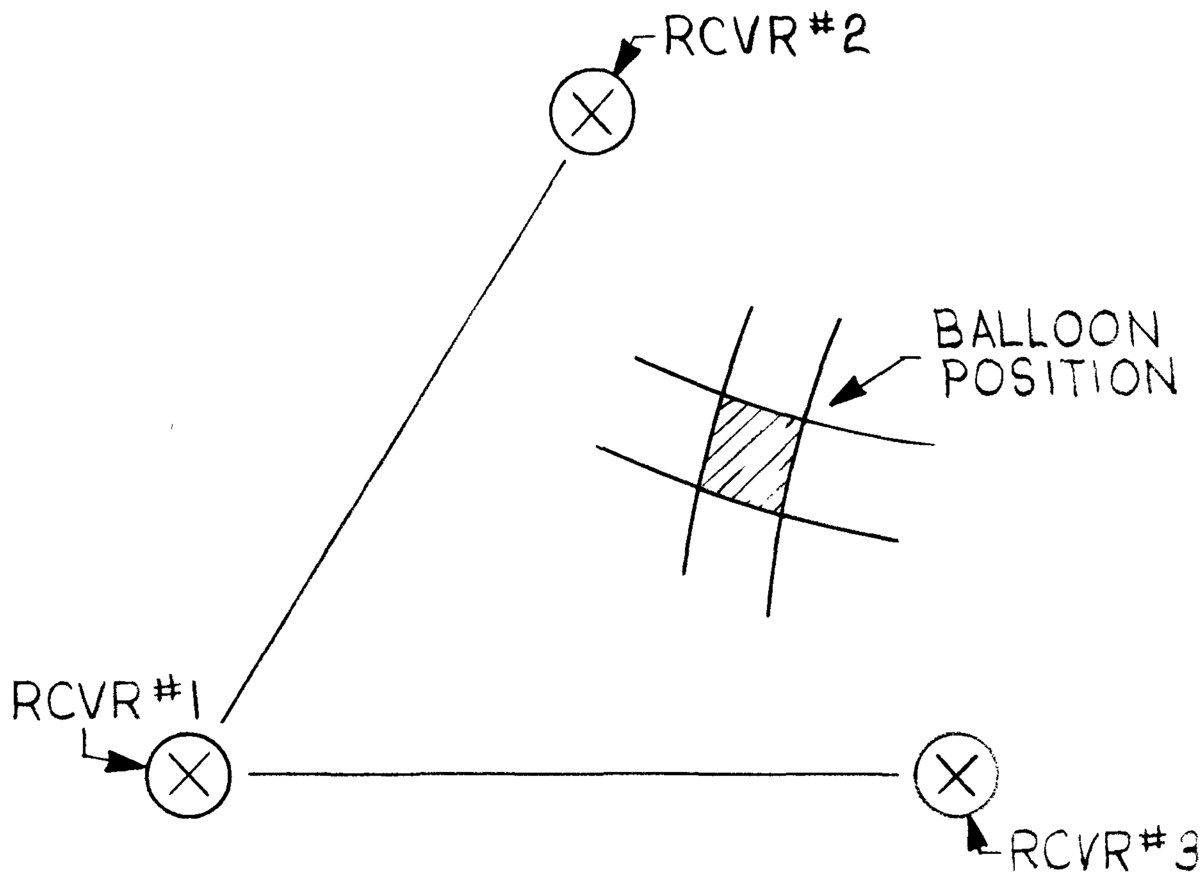


FIGURE 32. Intersecting Hyperbolas Formed by Two Receiver Pairs

Using more than four receiver stations adds redundancy so that the momentary loss of a receiver doesn't effectively terminate a flight. Whereas four receivers yield one physical solution, five receivers yield five, six receivers yield fifteen and seven receivers yield thirty-five solutions.

B. Effect of Geometry

As can be seen in Figures 31 and 32, the spacing between hyperbolic shells depends upon geometrical position. Only on the line between each pair of receivers is the separation of the shells as small as λ/M. Clearly the accuracy of the computed position depends upon the spacing of the shells as well as the orientation of the foci (receivers) with respect to each other and to the position of the transmitter. Maximum practical resolution inside the receiver array is achieved by deploying an equally spaced ring of receivers about a central receiver. A minimum receiver array should consist of a triangle of receivers with one in the center. The centrally located station is very important in giving good vertical resolution. When there are more than a minimum set of four receivers operating properly over some time interval, some of the solutions will be better than others because of the differences in the geometry.

Well outside the borders of any receiver array, the hyperbolic shells tend to become nearly parallel to one another. This implies that the uncertainty in computing position of the transmitter grows as the balloon drifts away from the array. The uncertainty is largest in the radial direction. Increasing the averaging times in determining the winds outside of the station array will help to decrease the effect of the position uncertainty.

C. Sources of Error

There are two primary sources of error which can affect the METRAC solution: count errors and station location errors. Count errors can come from a variety of sources, some interrelated. The most serious errors would arise if either the balloon or reference transmitter were interrupted even momentarily. This would cause dropped counts at all receiver stations simultaneously so that no solution could be computed.

Count errors will also occur if the frequency difference (reference and balloon transmitter) tracking filter loses lock at any receiver. This will happen whenever the signal to noise ratio at the receiver becomes sufficiently small for an appreciable part of the time constant of the filter. Experience during the Minneapolis field tests showed that this situation occurred most often when the transmitter was high and nearly directly above a receiver station or when the transmitter was far (30-100km) from the receiver. If the signal to noise ratio becomes small for a very short period of time, errors may occur in the counting even though the filter track remains locked to the frequency difference. Tests performed with a static transmitter showed that this type of error was generally random with magnitude of only one or two counts. Errors in FD_o counts can also occur due to sampling uncertainty. However, these errors are non-accumulative and are also on the order of only one or two counts per sample.

An error from any of these sources will locate the balloon transmitter between the wrong hyperbolic shells. If the error is not random, as is the case for the first two errors described above, the position error will grow as the balloon gets further away from the array and the hyperbolic shells get further apart. Random errors due to sampling uncertainty or occasional count errors will add artificial variance into the true position, but unless the balloon is well outside the baseline where the shells are far apart, this error in velocity is small when even computed over very short time intervals.

In addition to position errors due to inaccuracies in the count of the multiplied offset frequency difference, errors also arise from uncertainties in the locations of the receiver stations themselves. The solution to the METRAC positioning problem requires frequency counts at a minimum of four receivers as well as initial launch coordinates relative to the receiver array. Because of the extreme resolution inherent to the tracking system, an error of ten meters in the location of one station relative to the rest can be equivalent to as much as a 100 count sampling error. As the balloon moves away from its starting location, the position error will grow because the hyperbolic shells become more widely spaced as was discussed above.

Figures 33 and 34 present the results of a computer simulation of position errors caused by the mislocation of receivers. Figure 33 shows a triangular array of receivers with an X-Y plot of the trajectory of a balloon launched from the central receiver station. The balloon is carried outside of the receiver array at a height of about 2200 meters. Figure 34 presents three examples of how the computed height deviates from the true height of the transmitter after three sets of rectangularly distributed random errors ranging from -1 to +1 meters have been added to each coordinate of each receiver station. An error in the launch location with respect to a perfectly specified set of receiver stations causes similar errors.

D. METRAC Solution

Several techniques have been utilized to solve the basic hyperbolic navigational equations. Relatively straight forward iterative solutions are discussed by Kanter (1962) and Newton (1967). Newton (1967), Razin (1967) and Glish (1971) describe various closed-form solutions with varying degrees of complexity and

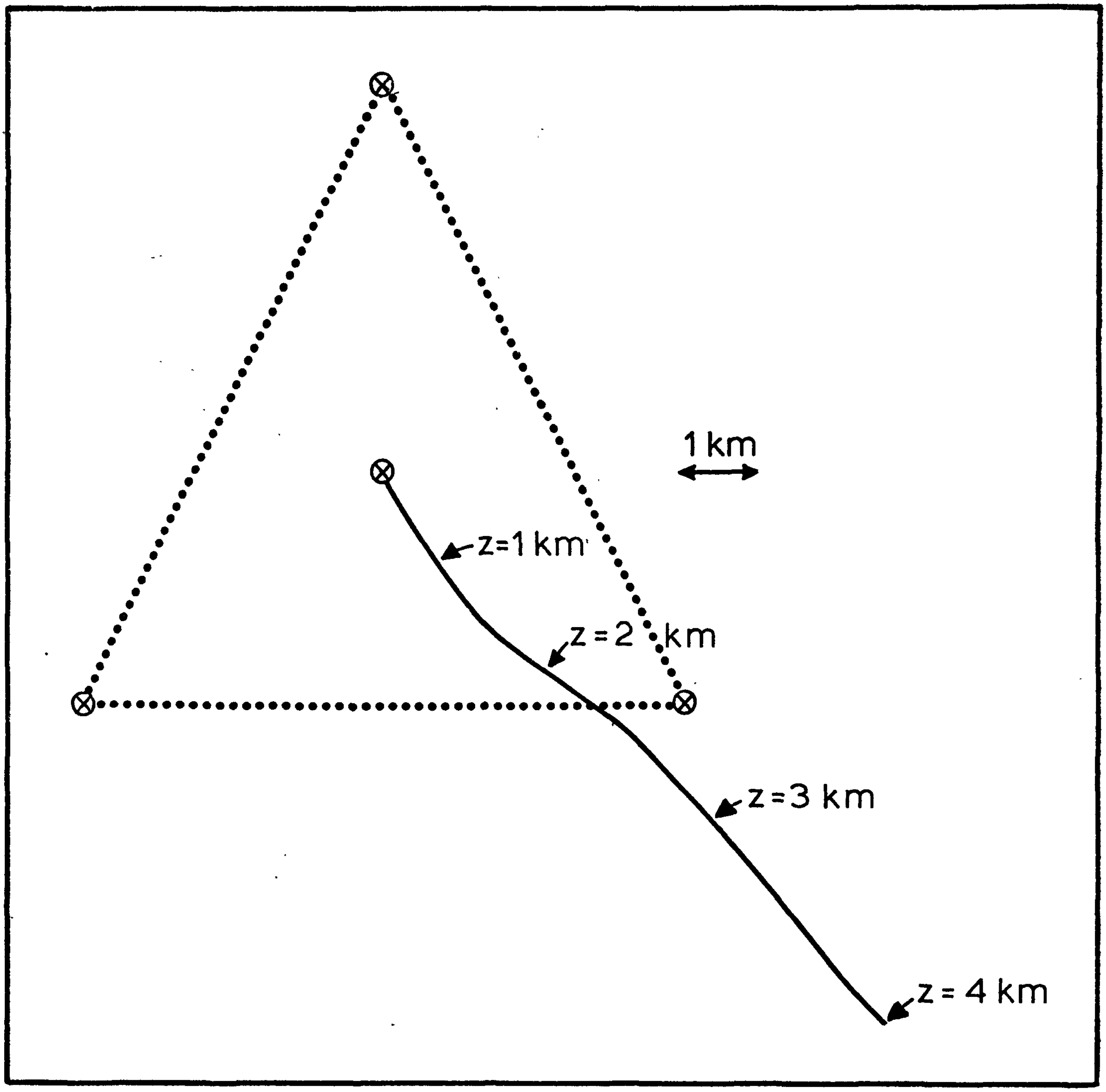


FIGURE 33. SAMPLE BALLOON TRAJECTORY FOR TRIANGULAR RECEIVER ARRAY

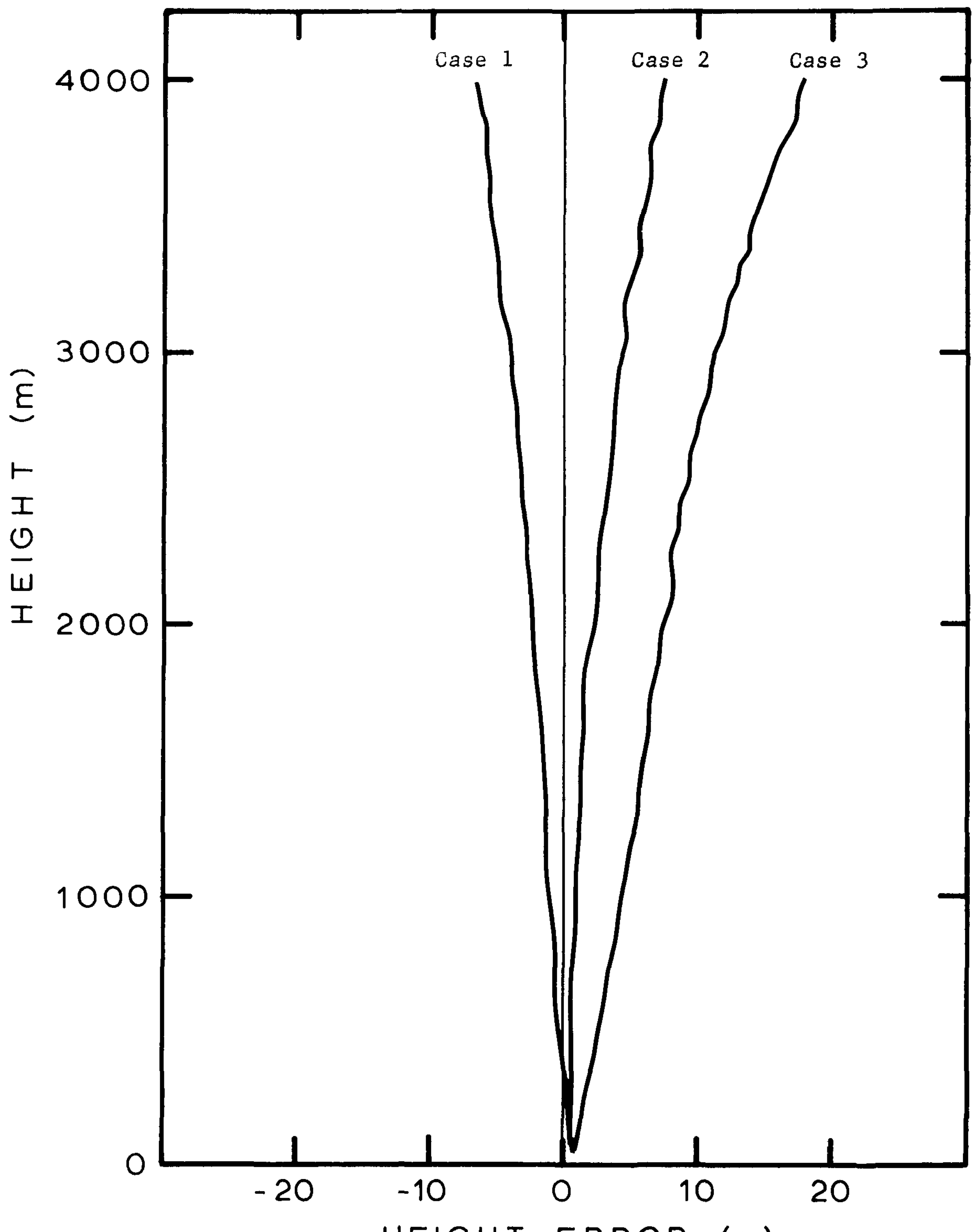


FIGURE 34. THREE EXAMPLES OF HEIGHT ERROR VERSUS HEIGHT FOR RECEIVER POSITION INACCURACY. RANDOM ERRORS TAKEN FROM A RECTANGULAR DISTRIBUTION (-1, 1) WERE ADDED TO EACH KNOWN RECEIVER LOCATION.

accuracy. More recently a novel approach has been developed by Schmidt (1972), and it was this method which was used to compute the METRAC solutions.

The classical formulation of the navigational problem is to determine a position when the range difference to two known stations is measured. Schmidt showed that the problem could be alternatively formulated in that the desired solution is the focus of a general conic whose major axis is defined in terms of the differences in range to three known stations. This method is particularly attractive not only because it is a closed-form solution, but also because it reduces the basic problem to solving a set of simultaneous linear equations.

E. Software

1. Software Input

The recorded data output from the METRAC command site consist of one second values of accumulated (multiplied and offset) frequency difference counts between the balloon-borne transmitter and the reference transmitter measured at each receiver site, FD_o, as well as status information from each receiver. The numbers of relevance in computing the balloon position are the accumulated Doppler counts, a small part of FD_o. The bulk of FD_o is due to the normal quasi-constant difference in frequency between the balloon and reference transmitters and is common to all receivers during each sample. By forming the differences of FD_o between pairs of receivers, this large component cancels out leaving the desired Doppler difference counts. All status information is also used to evaluate the quality of each data sample.

Status consists of the following:

1. Reference signal acquired
2. AFC
3. Filter track
4. $F_d < F_d$ MIN
5. $F_d > F_d$ MAX

The first three status bits are normally 1 and the latter two are normally 0.

2. Program METRAC

Figure 35 shows a general flow diagram of the METRAC software package. The following sections briefly describe each of the blocks of this diagram.

- METRAC

Program METRAC is the primary controller to the program flow. During the first pass, initialization and definition routines are called. Subsequently METRAC cycles until either a flight duration limit (ITIME) or an end-of-file is encountered.

- READIN

Subroutine READIN inputs the following initial data:

(1) Flight identification - 80 characters of free field alphanumeric characters.

(2) Number of receiver stations used.

(3) Serial number and relative x, y, z location of each receiver station.

(4) Transmitter frequency (403 MHz).

(5) Frequency multiplication factor (8).

(6) Flight duration limit (seconds).

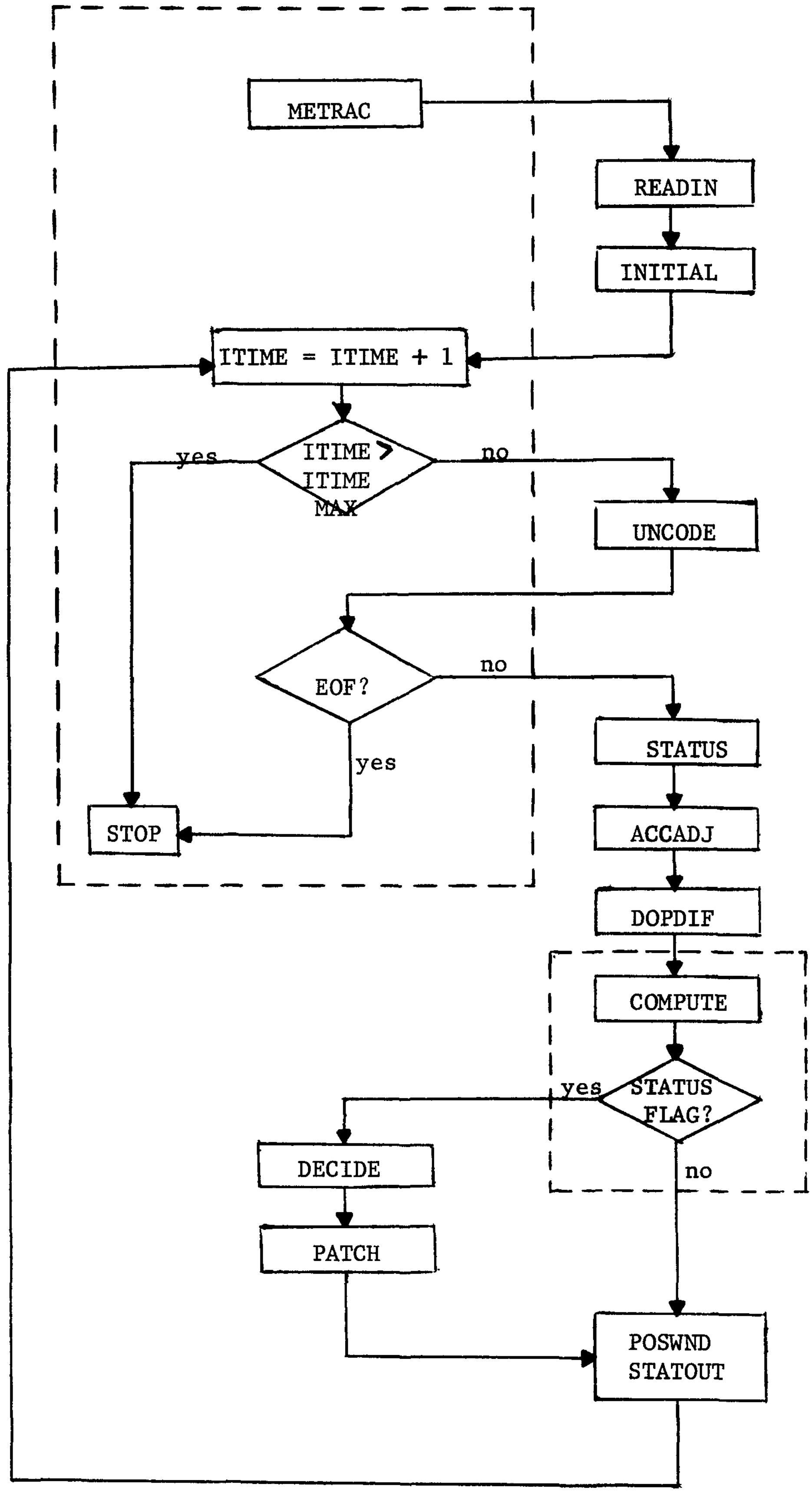


FIGURE 35: FLOW DIAGRAM OF METRAC SOFTWARE PACKAGE

- INITIAL

Subroutine INITIAL computes all the initialization and construct parameters used throughout the remainder of the computations. These include:

(1) Effective wavelength (wavelength/multiplication factor).

(2) Distances between each pair of receiver stations.

(3) Distances between launch point and receiver stations.

(4) Initial difference frequency accumulator values.

- UNCODE

Subroutine UNCODE reads a record (one second sample) of data from magnetic tape and decodes it to yield the accumulator and status data.

- STATUS

Subroutine STATUS determines which receivers have had status bits during the sample so that they will not be used in computing the transmitter position.

- ACCADJ

Subroutine ACCADJ differences the new accumulator values from the previous value and adds them to a bank of working accumulators. The working accumulators are structured such that the difference between any two of them is proportional to the difference in distance from the receivers to the transmitter.

- DOPDIF

Subroutine DOPDIF forms the Doppler differences between all pair of receivers.

- COMPUTE

Subroutine COMPUTE used the input station locations and the Doppler differences to compute all possible METRAC transmitter positions. If all seven receivers send valid data, 35 solutions are computed for each time sample.

- DECIDE

Subroutine DECIDE uses a primitive scheme of maximizing Doppler differences in choosing the "best" solution obtained from COMPUTE.

- PATCH

Subroutine PATCH uses the solution obtained from DECIDE to compute a new accumulator value when a receiver has had a status error. That receiver can then again be used in subsequent samples.

- POSWND and STATOUT

Subroutines POSWND and STATOUT print out all position, wind and status data computed for each sample.

VII. MINNEAPOLIS FIELD TEST

This chapter presents the results of a field test of the METRAC System conducted in Minneapolis by Control Data Corporation. The test was performed in order to complete the evaluation of the feasibility of utilizing METRAC to obtain accurate detailed measurements of the urban wind field. Since no radar data was available for comparison with the METRAC data, the only independent verification of the system's accuracy was obtained by comparison with winds derived by tracking a radiosonde package attached with the METRAC package to the same balloon. For this comparison a WeatherMeasure RD-65 rawinsonde system was borrowed from the University of Wisconsin.

A. METRAC™ Deployment for the Minneapolis Test

Planning for the METRAC test began in December. It was decided to locate the reference transmitter on top of the IDS tower and a lease was signed with Chicago Broadcast Services. The reference antenna was installed after the first of January and transmitter equipment was installed about a month later.

The following sites were selected as suitable locations for METRAC receivers:

(1) Control Data
Roof of South Tower
Minneapolis, Headquarters

(2) Radisson South
7800 Normandale Blvd.
Bloomington
South Penthouse Roof

(3) Prudential Insurance
North Central Home Office
3701 Wayzata Blvd.
Minneapolis
Tower roof

(4) Kenneth S. Gage (private home)
4833 Aldrich Avenue So.
Minneapolis
30 foot tower guyed to roof

(5) Model Ready Mix Co.
400 W. 61st Street
Minneapolis
Top of radio tower

(6) General Communications - St. Paul Shop
756 N. Snelling
St. Paul
Top of radio tower

(7) Imperial Heights Apartments
90 Imperial Dr.
West St. Paul
Tripod on roof

Figure 36 shows the locations of the reference transmitter and the receivers on a map of the Twin Cities. Each R on this figure represents the location of a receiver and X represents the location of the reference transmitter. Installation of the receiving equipment was completed for six stations by the end of February and the seventh station was added in the middle of March. A network of leased telephone lines was installed by Northwestern Bell to connect each receiver to the command site which was located in the Research Division's METRAC laboratory.

A cassette tape recorder was set up at the command site to record raw data from the station network. Equipment was also set up to enable the transfer of raw data to a format which could be read directly into the CDC 6600. In order to compute the location of the mobile transmitter the METRAC algorithm requires the initial position of the transmitter and the relative locations of all receiver sites. For the purposes of the Minneapolis test this information was obtained from survey maps which are available from Municipal, County and State Survey Offices. Of special value were the "100-scale" maps from which horizontal location can be determined to within a few meters. These maps also contain elevation

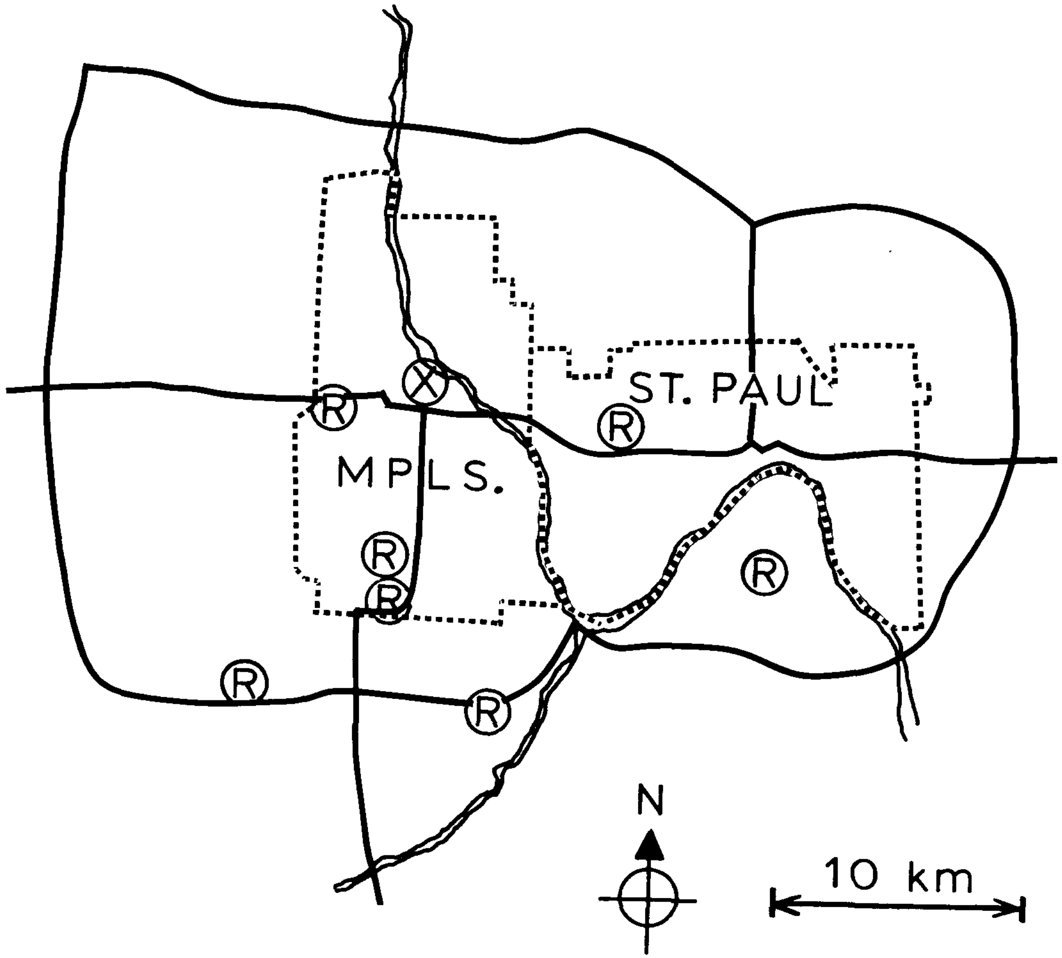


FIGURE 36. MAP OF INSTALLATIONS FOR TWIN CITIES TEST

contours every two feet. Coordinates for all locations were compiled in the Minnesota State grid-south zone in order to provide a common frame of reference for all stations. No special survey was attempted for the METRAC receiver locations and therefore the uncertainty to which these locations are known remains a few meters. Since systematic errors are known to result from location errors of station position, an accurate survey is important for system calibration.

B. Preliminary System Tests

The METRAC System was deployed for the field test late in February. Less than two weeks were required to install receivers at six sites, to install the reference transmitter, and to check reception at each receiver site. The latter was accomplished by comparing the strength of signals received from the reference transmitter and from a transmitter installed at the balloon launch site, (on top of the Radisson South Hotel) with the strength computed for free-space propagation.

As soon as several receivers had been installed, a system performance was checked by acquiring the reference signal at each receiver and locking on to the second transmitter located on top of the hotel. The commands to acquire reference and lock were given from the command site. Our first indication that the system was working properly came from the observation that the difference frequencies between each pair of receivers were nearly identical.

Satisfied with the results of the static test, our next step was to record data as the METRAC transmitter was moved along a prescribed path on top of the penthour roof of the hotel. The results of this walk are shown in Figure 37 where every one second data point is plotted. There seems to be a systematic discrepancy of about a meter between the path walked and the path computer by METRAC. Such an "error" may be due to the fact the transmitter was secured at the end of a long

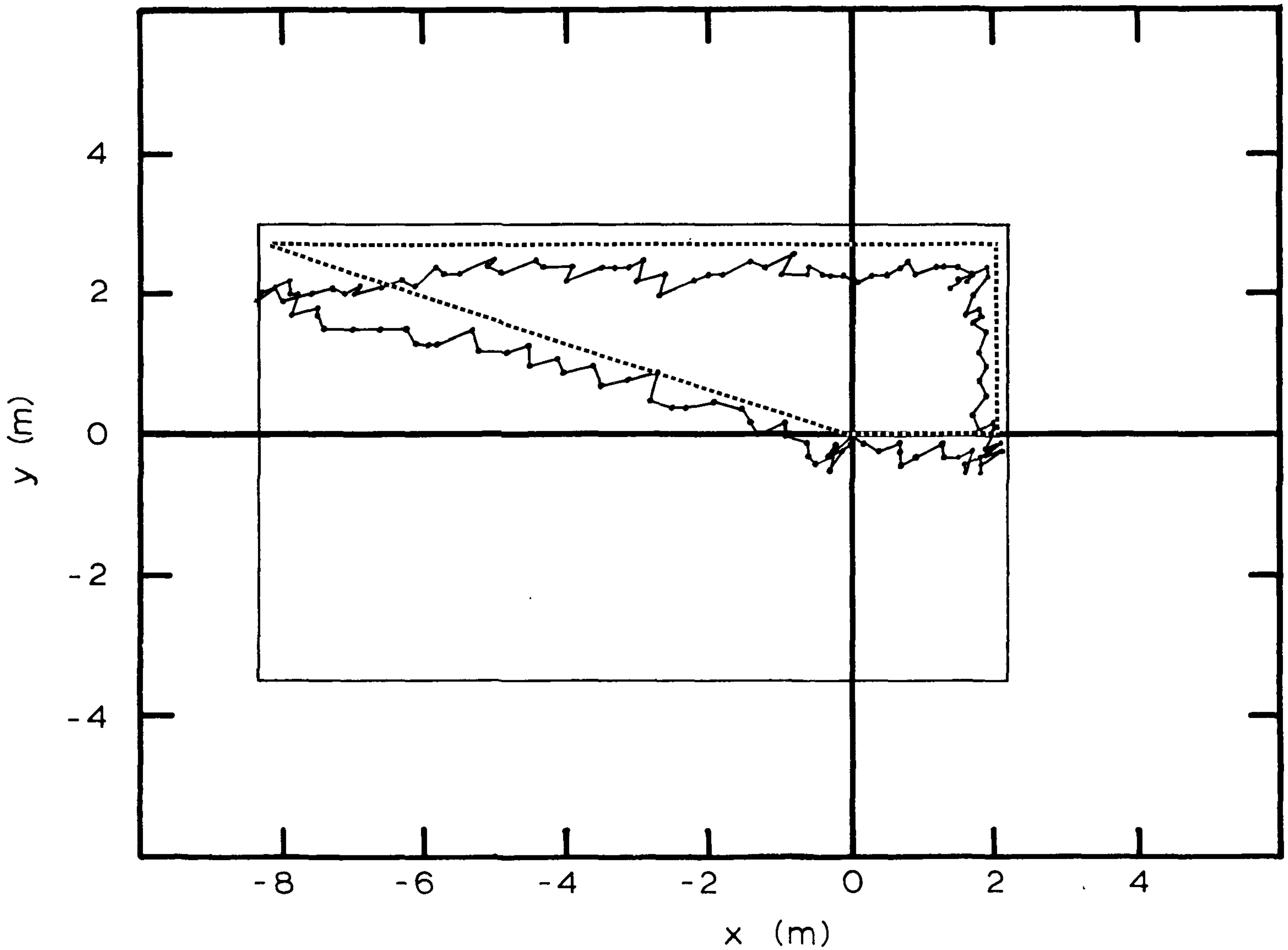


FIGURE 37. X VS Y PLOT OF WALK ON PENTHOUSE ROOF OF RADISSON HOTEL WITH DATA PLOTTED AT 1 SECOND INTERVALS.

hand-held pole which is difficult to hold exactly vertical. Another possible explanation is the position location errors mentioned earlier and the need for system "Calibration" by more accurately surveying receiving antenna locations.

The data that were recorded from these preliminary system tests provided the first realistic test of the data processing system.

C. Wind Profile Comparison Tests

A test was carried out in the Minneapolis area during April 1974 to compare wind profiles obtained from the METRAC system with wind profiles obtained from rawinsonde and theodolite measurements. During this period, eight balloons were launched from the top of a 22 story suburban hotel. Each balloon carried both the lightweight METRAC transmitter and a standard 1680 MHz VIZ radiosonde. The radiosonde package was tracked with a portable WeatherMeasure RD-65 rawinsonde system on loan from the University of Wisconsin Department of Meteorology, Madison, Wisconsin. In addition, a theodolite was used to track the balloon optically when cloud cover and visibility permitted. This section presents typical METRAC data and wind profile comparison data obtained in the Minneapolis test.

Figure 38 shows the x-y trajectories for the comparison data presented in this section. The locations of the seven receiver stations are also shown. The trajectories labeled MF3, MF4 and MF7 represent six minutes of data, and trajectories labeled MF2 and MF5 represent twenty-eight minutes of data. Both flights MF2 and MF5 extend well outside the receiver station array.

Figures 39 through 44 show the wind profiles computed for trajectories MF3, MF4 and MF7. Each of these figures presents the comparisons between METRAC derived

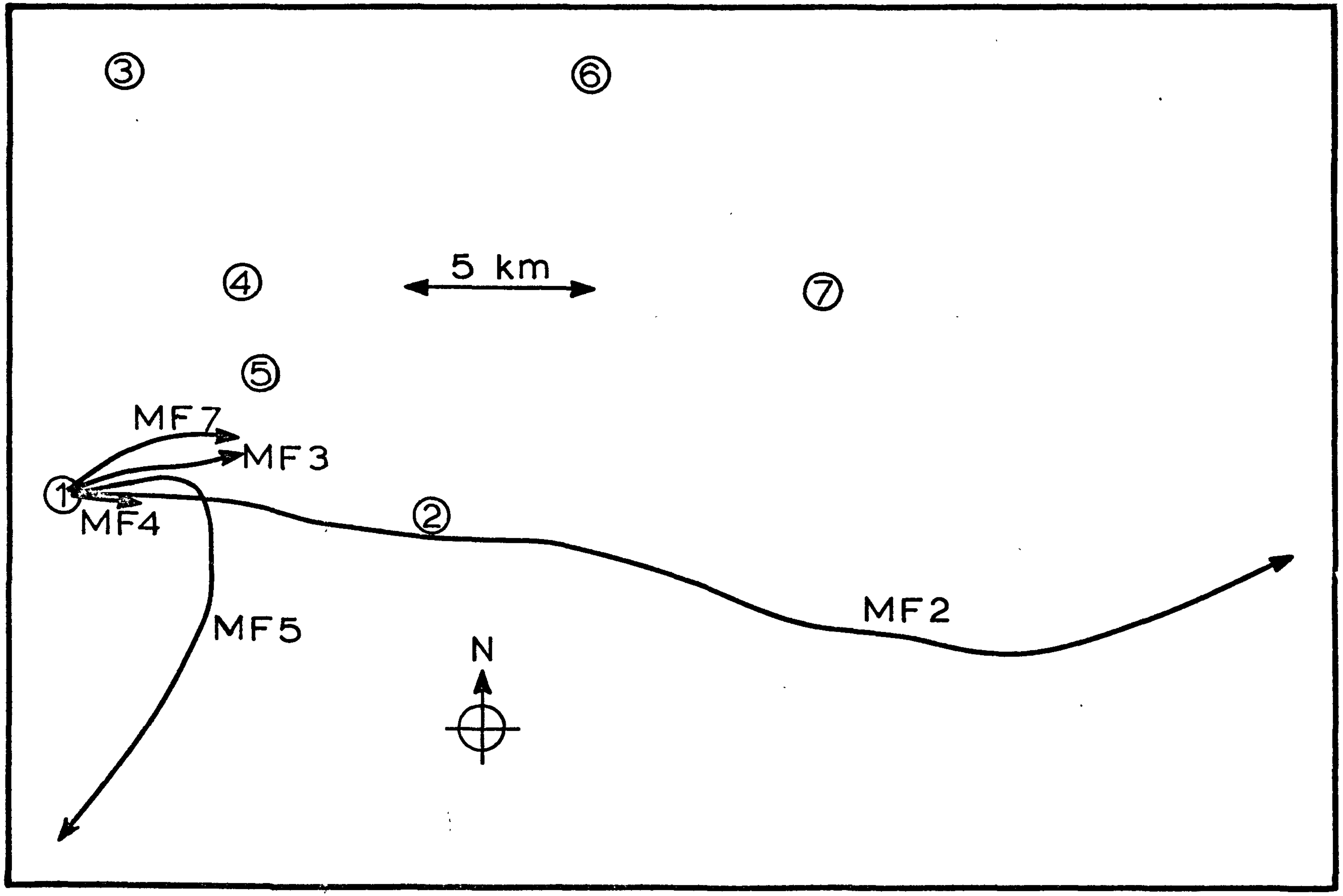


FIGURE 38. X-Y TRAJECTORIES FOR SELECTED TEST FLIGHTS

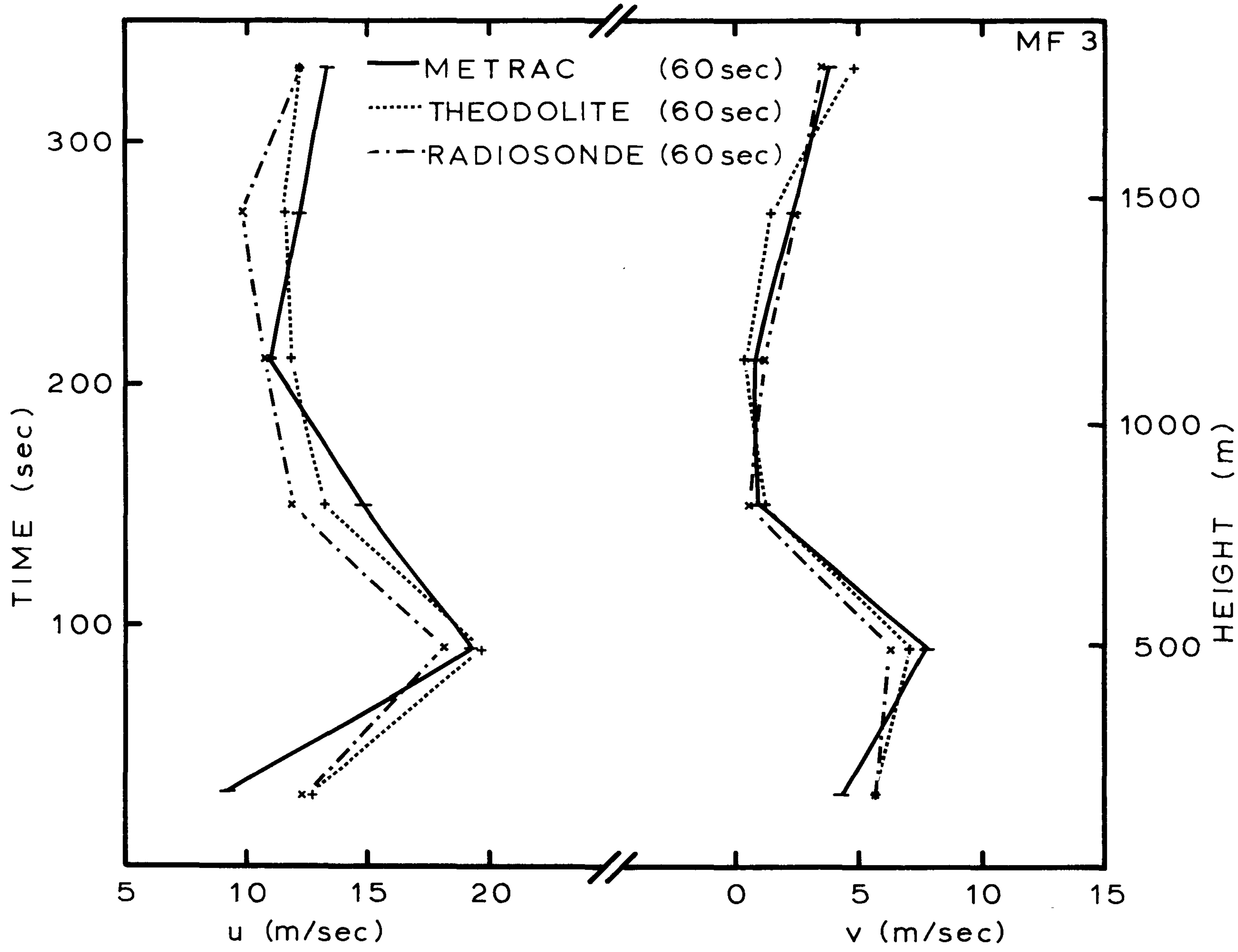


FIGURE 39. COMPARISON OF 60 SECOND WIND PROFILES FOR FLIGHT MF3

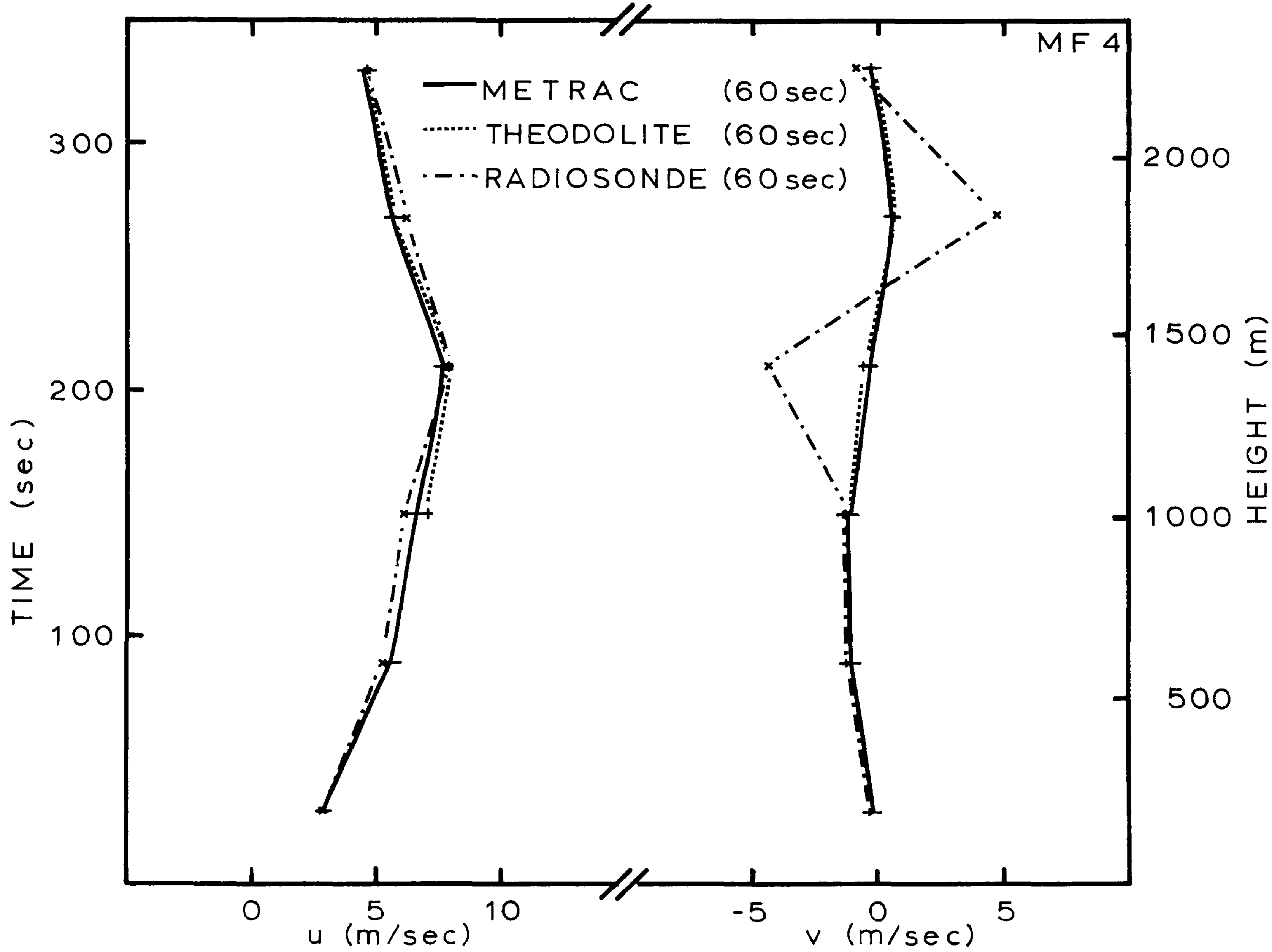


FIGURE 40. COMPARISON OF 60 SECOND WIND PROFILES FOR FLIGHT MF4

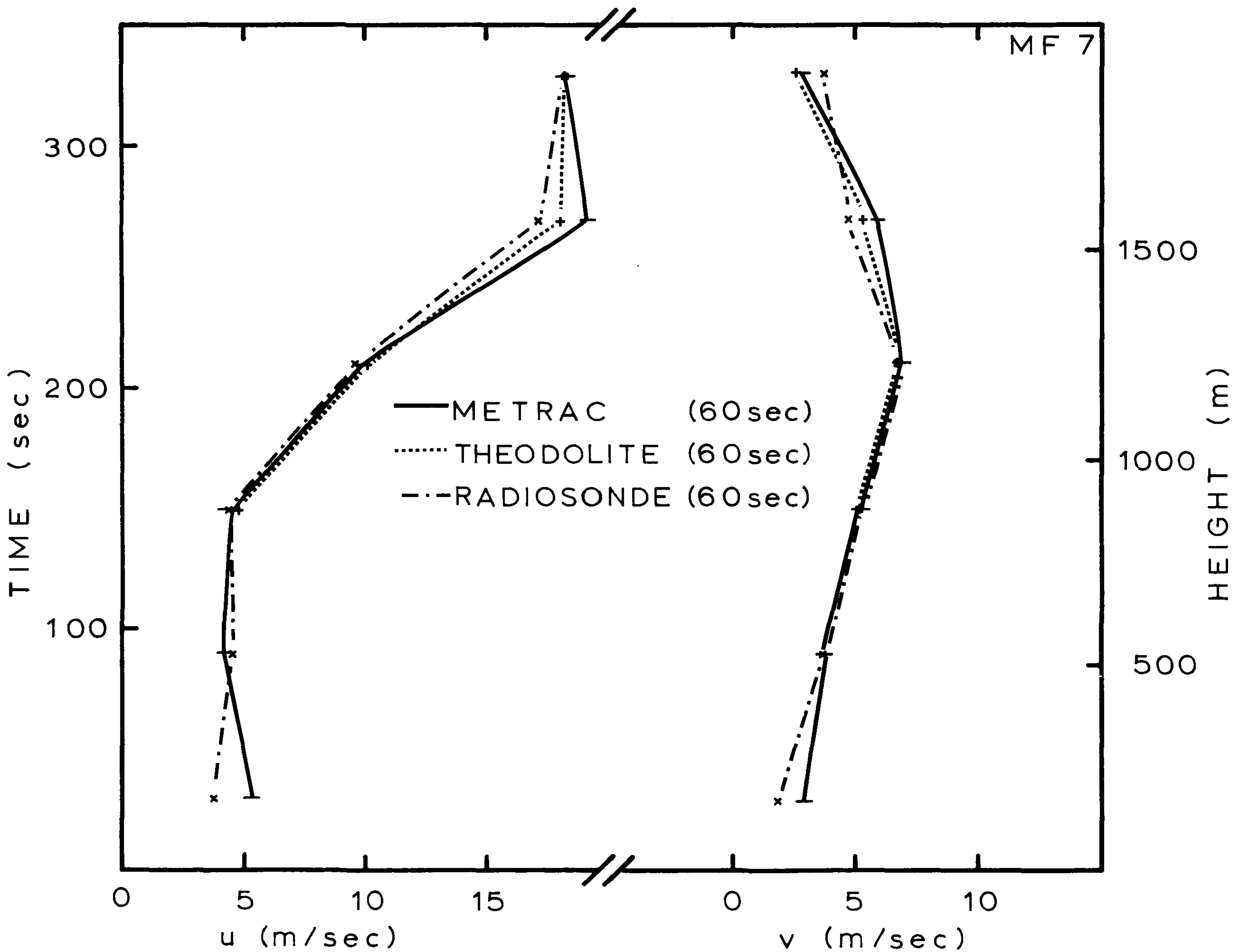


FIGURE 41. COMPARISON OF 60 SECOND *WIND PROFILES FOR FLIGHT* MF7

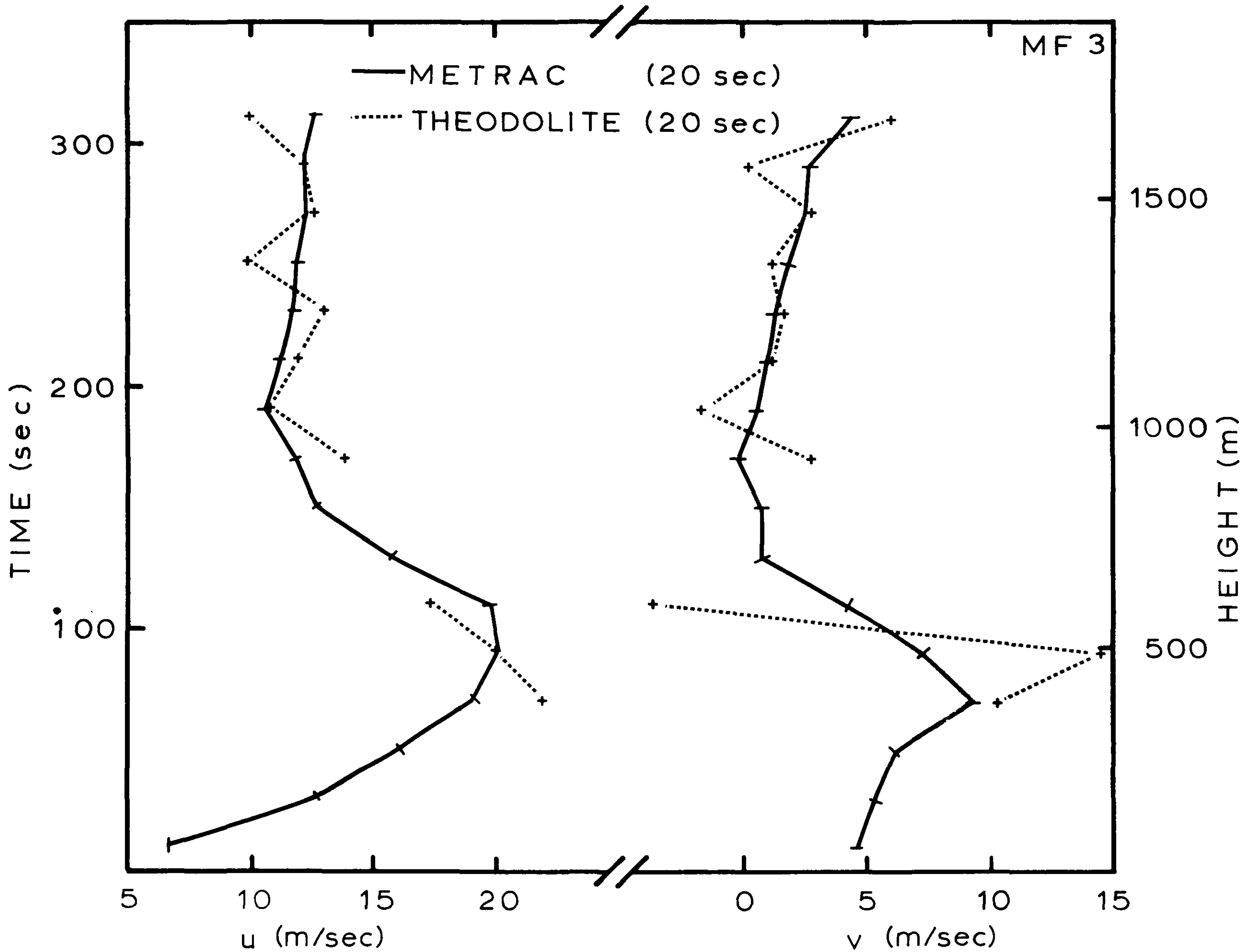


FIGURE 42. COMPARISON OF 20 SECOND WIND PROFILES FOR FLIGHT MF3

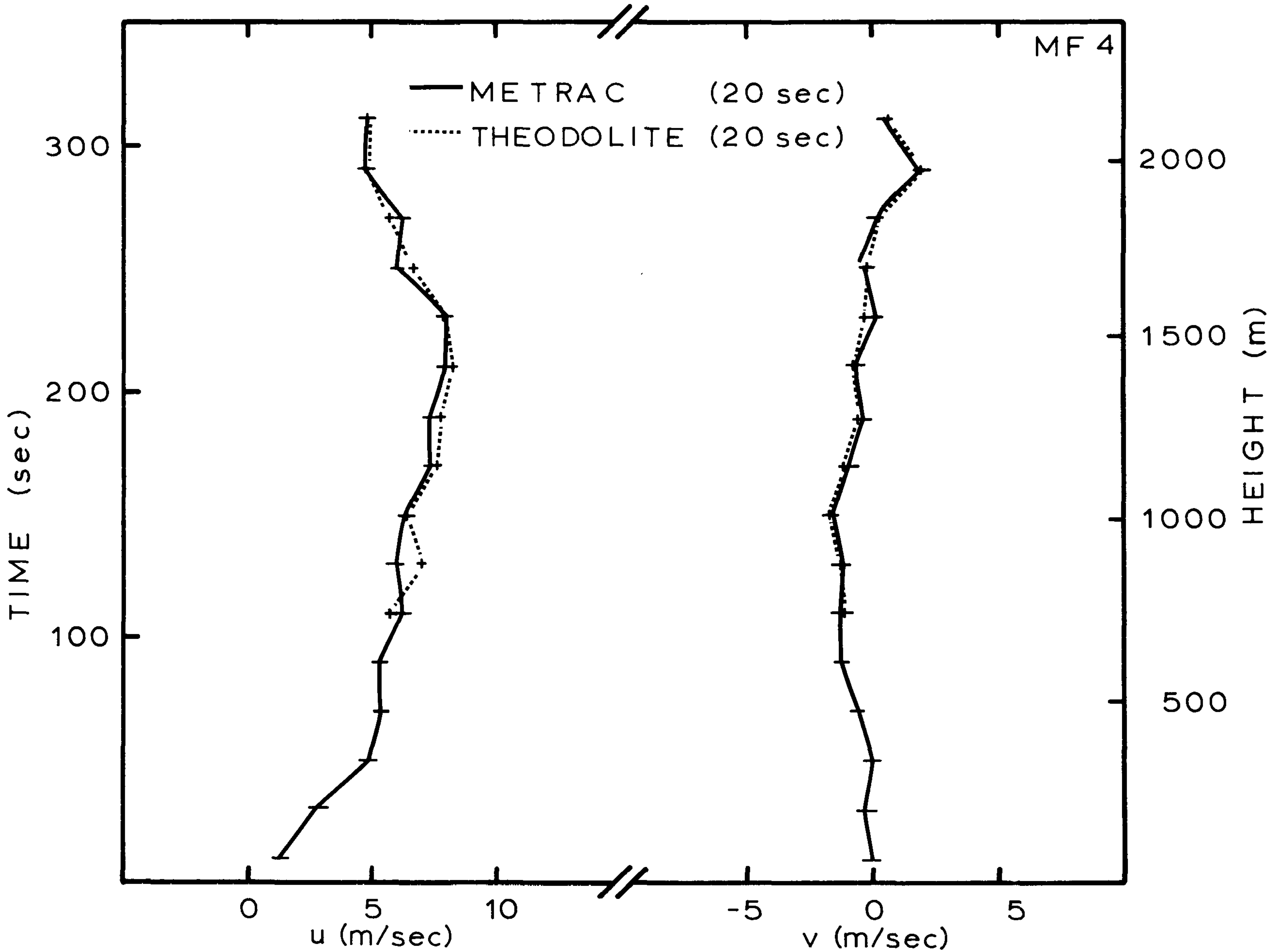


FIGURE 43. COMPARISON OF 20 SECOND WIND PROFILES FOR FLIGHT MF4

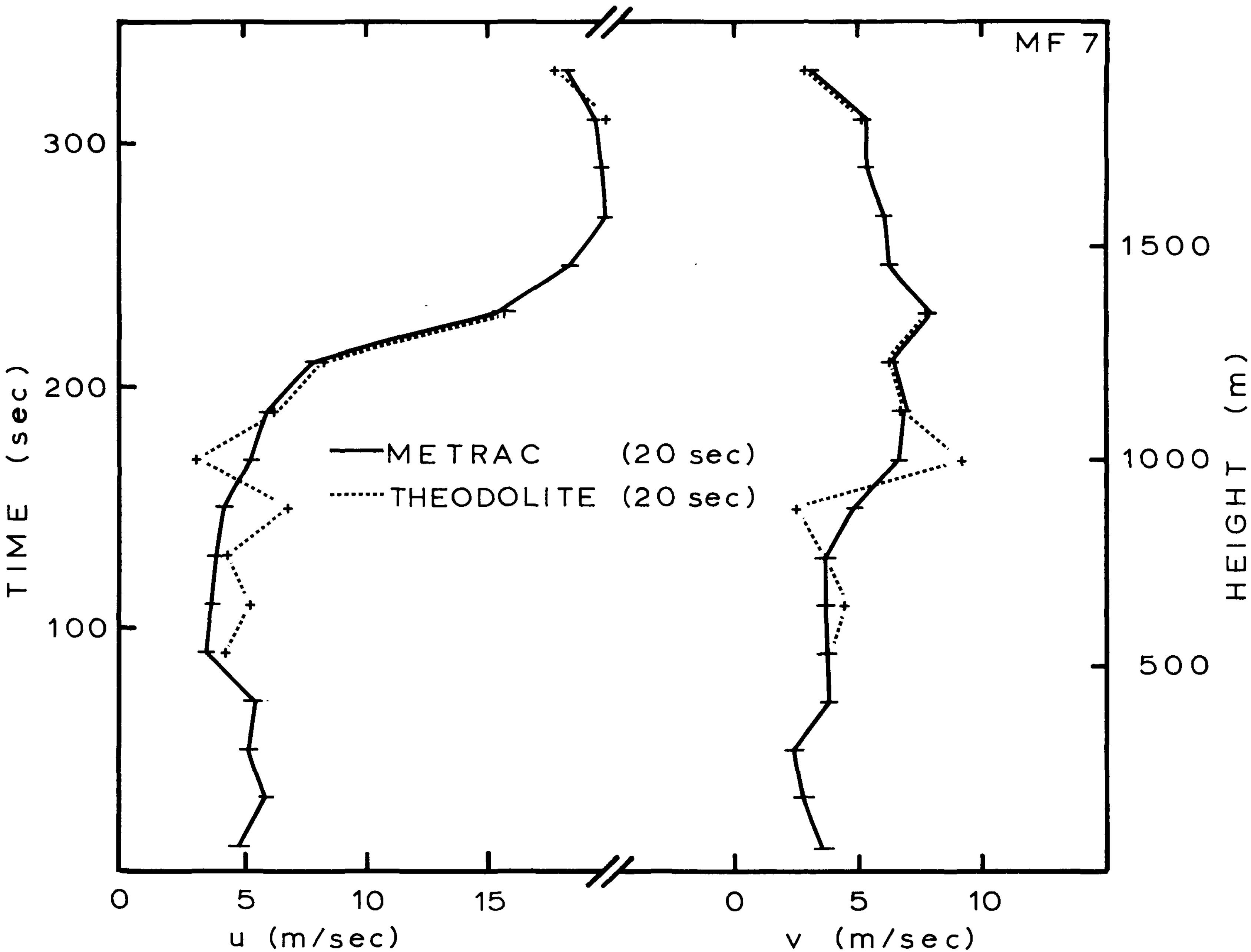


FIGURE 44. COMPARISON OF 20 SECOND WIND PROFILES FOR FLIGHT MF7

wind profiles and rawinsonde and theodolite derived wind profiles. Figures 39, 40, and 41 show the first six minutes of flight observations plotted once per minute, and Figures 42, 43 and 44 show the same flights with observations plotted at twenty-second intervals. Since rawinsonde measurements were taken only once per minute, they are not included in the latter figures.

Rawinsonde and theodolite winds are determined from measurements of elevation and azimuth angles and independently computed or inferred values of height. The accuracy to which a radiosonde system can determine these angles is dependent upon the beam size of the antenna. Great precision generally requires the use of large antennas and complicated pedestal machinery. The RD-65 rawinsonde system has a minimum resolvable element of 0.1^{o} and experience shows that the RMS error may be as large as several tenths of a degree. Optical theodolite tracking with an experienced observer is substantially more accurate with an RMS error of only a few hundredths of a degree. For comparison, the RMS error often associated with the GMD-1 rawinsonde system is 0.05^{o} (Danielsen and Duquet, 1967).

Uncertainties in the determination of the height of the balloon also affect the accuracy of the horizontal position computed from azimuth and elevation angles. This error is particularly significant at low elevation angles. For the Minneapolis tests, thermodynamic heights computed from the radiosonde data were used for both the rawinsonde and theodolite determined winds. Errors in timing the angular measurements also look exactly like height errors in the computation and are critical when the angular position of the balloon is changing rapidly. This problem is most serious in the early parts of the flight and with strong winds.

The errors described above can easily account for errors in the wind speeds of 1-3 m/sec for 60 second unaveraged rawinsonde winds. The errors will be largest in the radial direction due to uncertainties in balloon height and will be dependent on wind speed as described above. These facts may explain the largest discrepancy between METRAC winds and the rawinsonde winds which occur in the u component of Figure 39.

Because radiosonde heights were also used in determining the theodolite winds, the normal single theodolite pibal tracking assumption of a known constant ascent rate was unnecessary. This assumption is particularly bad near the earth's surface in an urban environment. Double theodolite techniques must be employed to compute accurate pibal winds such as those presented by Ackerman (1974). However, by using radiosonde heights, sixty-second theodolite wind errors should be smaller than 1 m/s. Figures 43 and 44 show excellent agreement between METRAC and theodolite winds even over twenty-second intervals except for isolated values which were read or recorded incorrectly.

METRAC wind accuracy is limited in a way very different from the rawinsonde or theodolite accuracy. The differential Doppler numbers locate the balloon borne transmitter between two hyperbolic shells found by rotating hyperbolas about an axis joining a pair of receivers (foci). The three-dimensional position can then be solved as the common volume formed by the intersection of three such regions. Clearly the best resolution in position is obtained when this volume is smallest, and this occurs when the hyperbolic shells intersect one another orthogonally. Position errors can be large when the intersecting shells are nearly tangent. The minimum spacing between two shells for the Minneapolis tests was 10 cm. When the transmitter is within the receiver array, the geometry of the intersections is favorable. Simulation studies show that expected accuracy for this case is within a few centimeters/sec for 10 second winds.

Actual errors in computed position and wind speed can occur if the Doppler cycles are not counted accurately. This happens when the signal to noise ratio becomes too small. In practice, this problem was uncommon and occurred only when the balloon transmitter was well outside the receiver array or located almost directly above a receiver. Utilizing more than the minimum number of four receivers circumvents this problem.

Errors in computed position can also arise if the relative locations of the receivers are not accurately known. This error is most serious for long flights when the transmitter moves across the entire array. However, this problem can be overcome by accurate station surveying.

Figure 39 thru 44 showed only the first six minutes of data or nearly two kilometers in height. This is the region of most direct interest in air pollution study. However, the METRAC system can track the transmitter to very high altitudes and distances well outside of the baseline as was shown by trajectories MF2 and MF5 in Figure 38. Figures 45 and 46 show the u and v wind components for these two wind profiles compared with the associated rawinsonde wind profiles. The agreement between the METRAC winds and the radiosonde winds is again excellent. In fact, one can observe the apparent increasing amplitude oscillations in the radiosonde winds in the top third of the wind profiles in both figures. These oscillations are due to increasing errors in positioning the balloon due to the fixed angular resolution of the rawinsonde system as well as the larger errors associated with low elevation angles. Both errors are characteristic of single dish tracking systems.

Errors in position computed from the METRAC system also degrade when the transmitter is outside the receiver array. This effect, however, does not generally become significant until one is several times the baseline of the receiver array outside of the array and is probably undetectable in sixty-second or even twenty-second wind profiles. For example, Figure 47 shows a comparison between twenty-second METRAC winds and twenty-second theodolite winds between 800 and 1150 seconds into flight MF5 (see also Figure 46). The comparison is excellent except for one bad theodolite reading at 960 seconds into the flight. The largest discrepancy is 1.2 m/s which, indeed, speaks well for the theodolite observer. The balloon is between 2 and 4 km outside of the receiver baseline and between 5 and 8 km from the launch point and theodolite during this period of data.

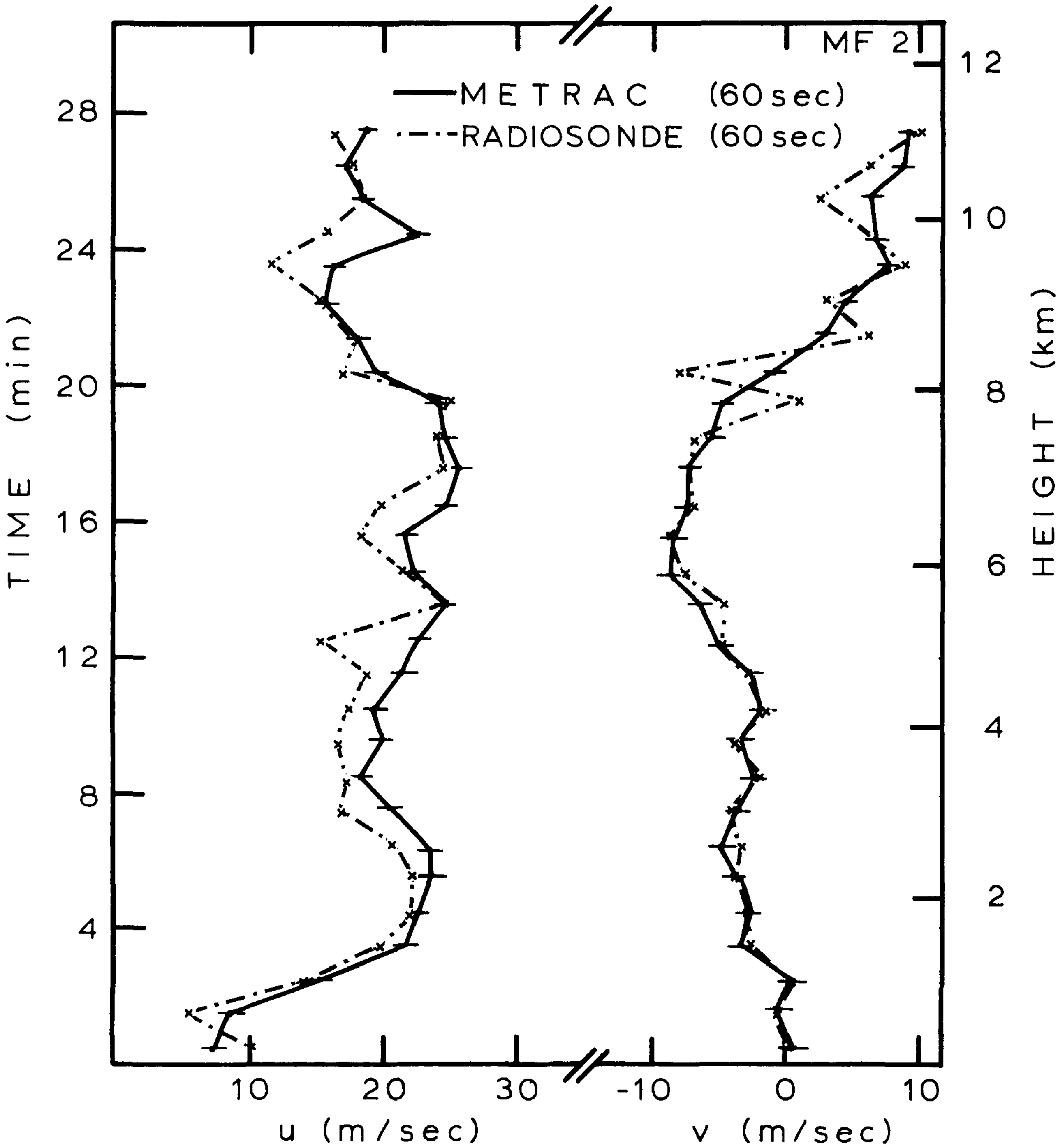


FIGURE 45. WIND PROFILES FOR FLIGHT MF2

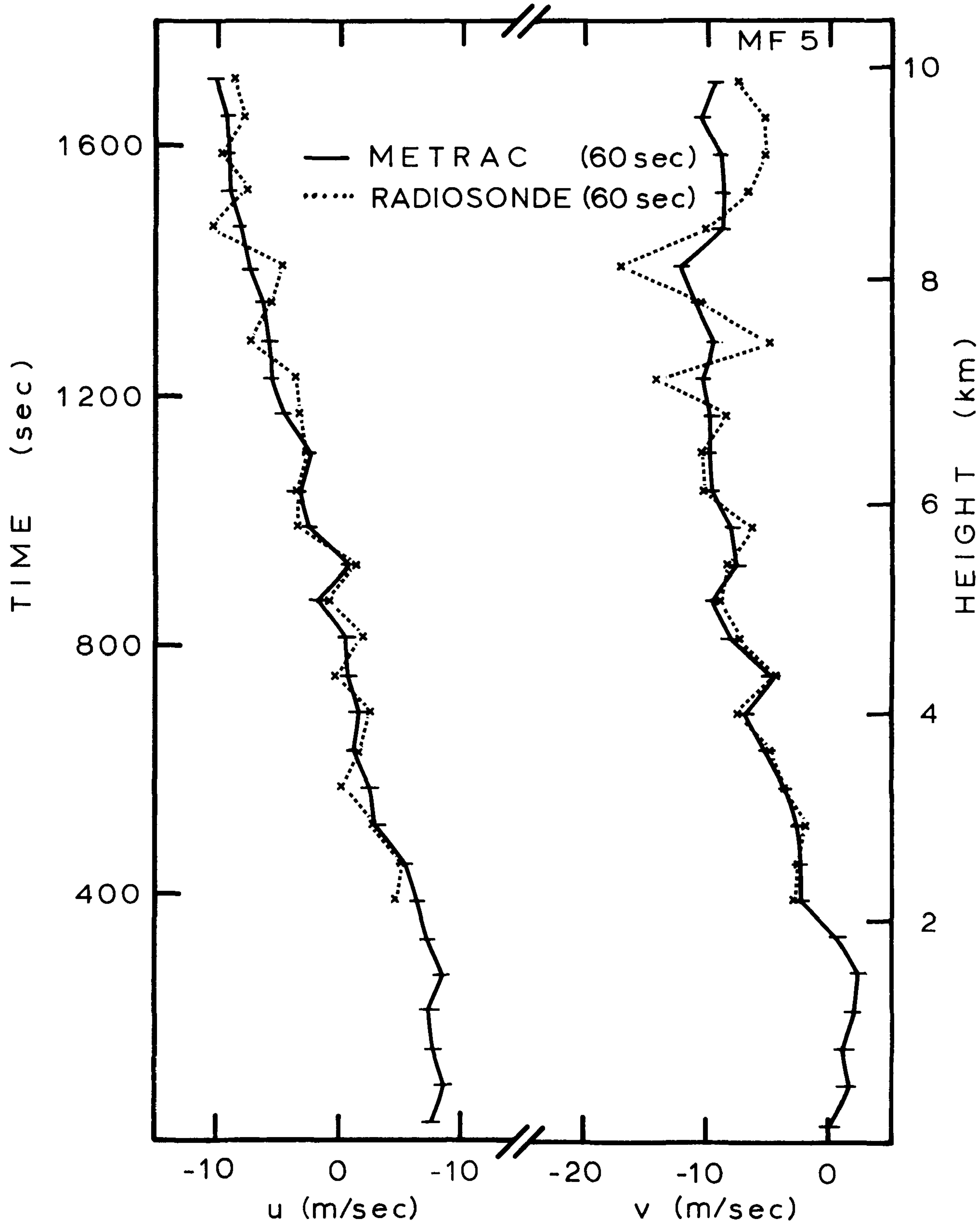


FIGURE 46. WIND PROFILES FOR FLIGHT MF5

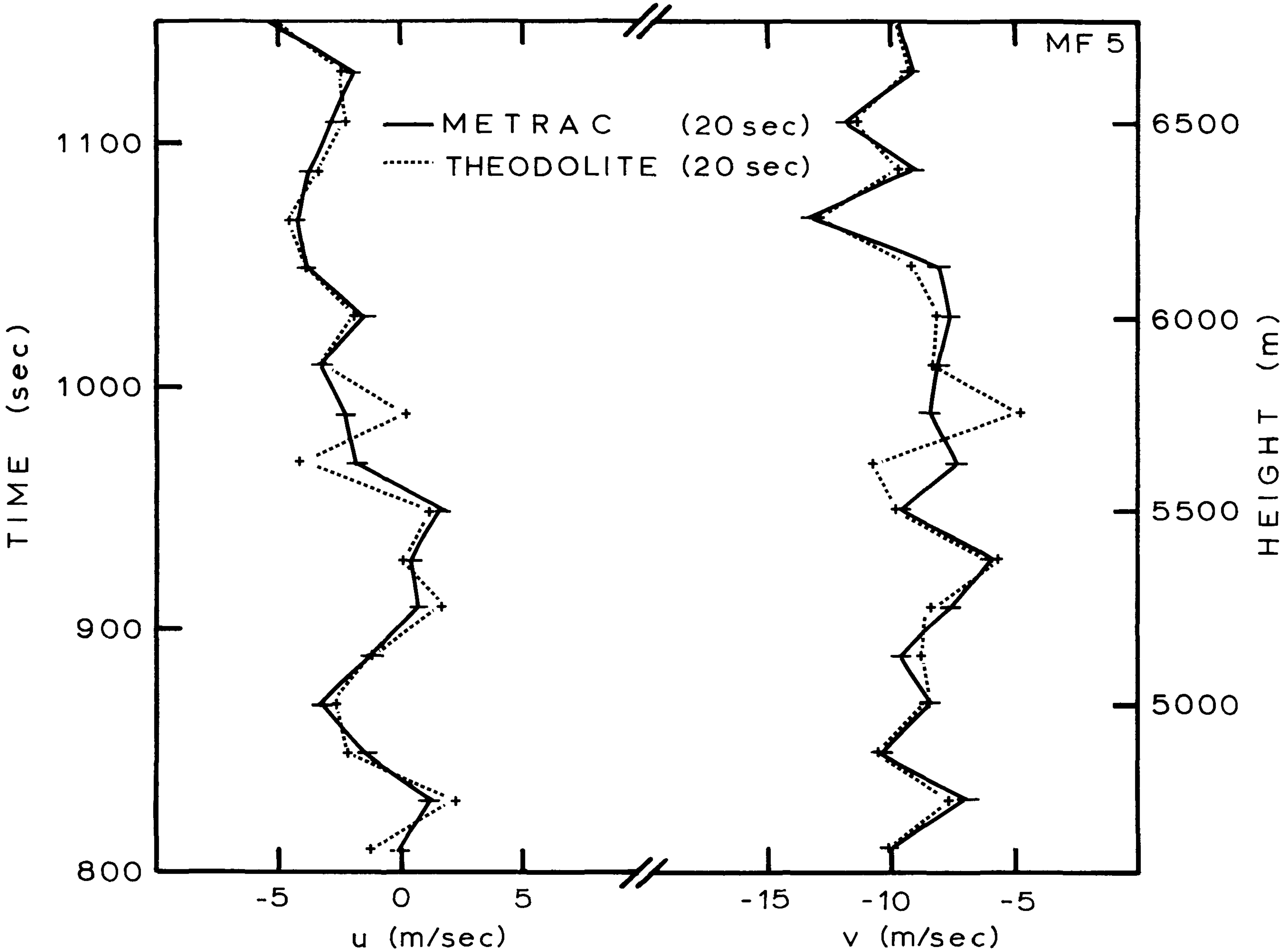


FIGURE 47. WIND PROFILES (20 SEC) FOR FLIGHT MF5

D. Special Capabilities of the METRAC System

Besides accuracy, one of the key features of the METRAC system alluded to above is the capability of small scale resolution. Relatively small scale structure can be exposed by decreasing the sampling interval. Figure 48 shows a rather unexciting profile of wind (v component) which is nearly zero up to 3.0km as measured by both the METRAC system and the rawinsonde system. Figure 49 compares sixty-second METRAC determined winds with thirty-second METRAC winds, while Figure 50 compares the sixty-second winds with fifteen-second METRAC winds. In each of these figures, the presence of a strong and relatively sharp shear layer emerges between 1 and 1.4km of height. Figure 51 illustrates this feature of high resolution again with an example from flight MF7. The strong shear present in the u component of the wind is shown to be concentrated in an extremely thin layer of approximately fifty meters depth.

Figure 52 illustrates the optimal resolutions of the METRAC system when position is computed for each one-second sample. This sixty-second segment of data with "wind" speeds plotted every second shows the circular rotation of the METRAC transmitter suspended below the balloon. The frequency and amplitude of this periodic motion agrees favorably with simple pendulum theory. The detail of the motion appears to be at least as good as the detail of the balloon induced oscillations which have been measured with the FPS-16 Radar/Jimsphere system and discussed by DeMandel and Krivo (1972). This kind of resolution encourages further evaluation of the use of the METRAC system to obtain measurements of atmospheric turbulence or of even looking more closely at the response dynamics of the balloon as it ascends through the atmosphere.

Another important aspect of the METRAC system is that the solution is based purely on geometry and the physical laws of electromagnetic wave propagation. In other words, determination of the three balloon coordinates x, y and z are made without

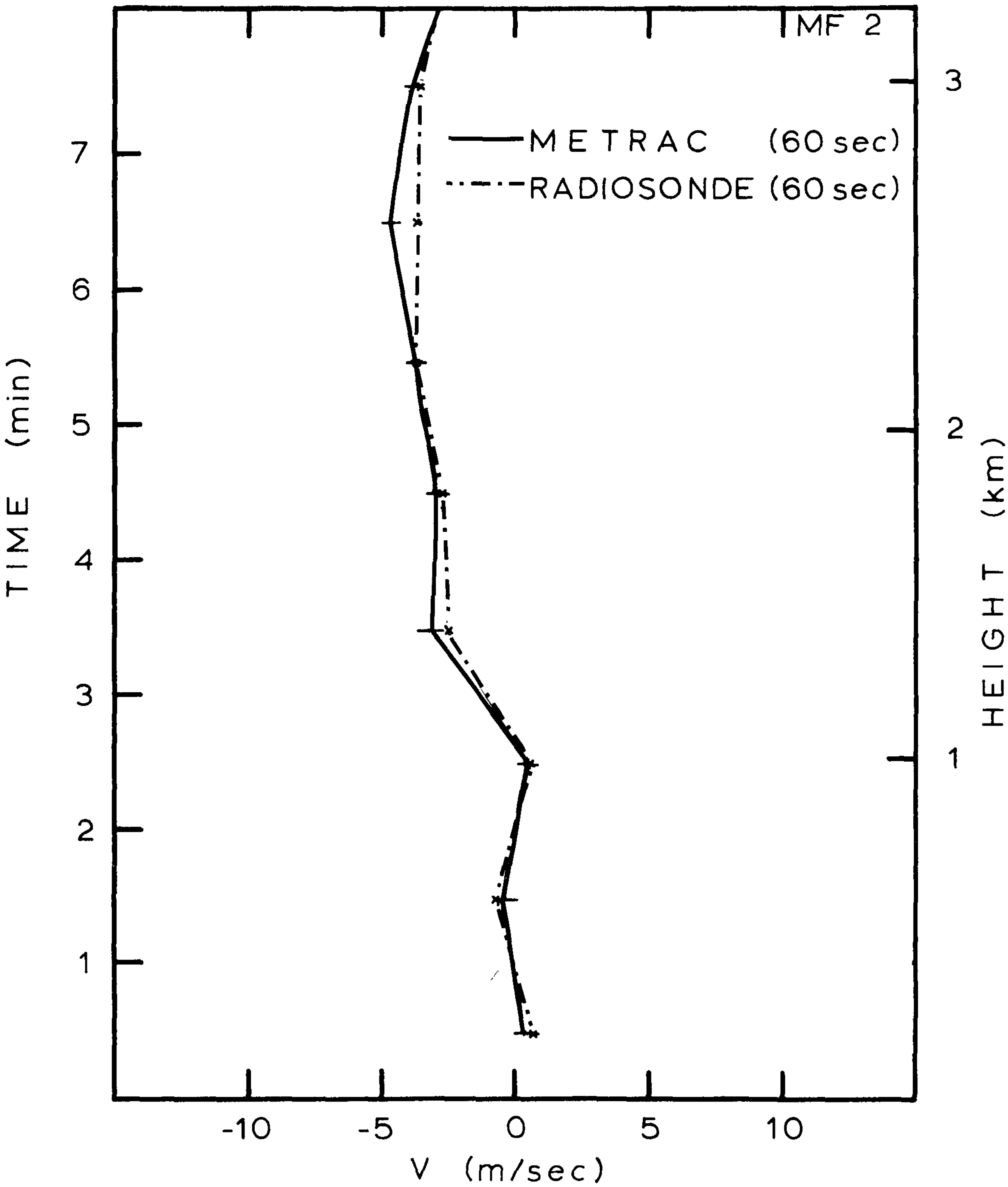


FIGURE 48. WIND PROFILE FOR FLIGHT MF2

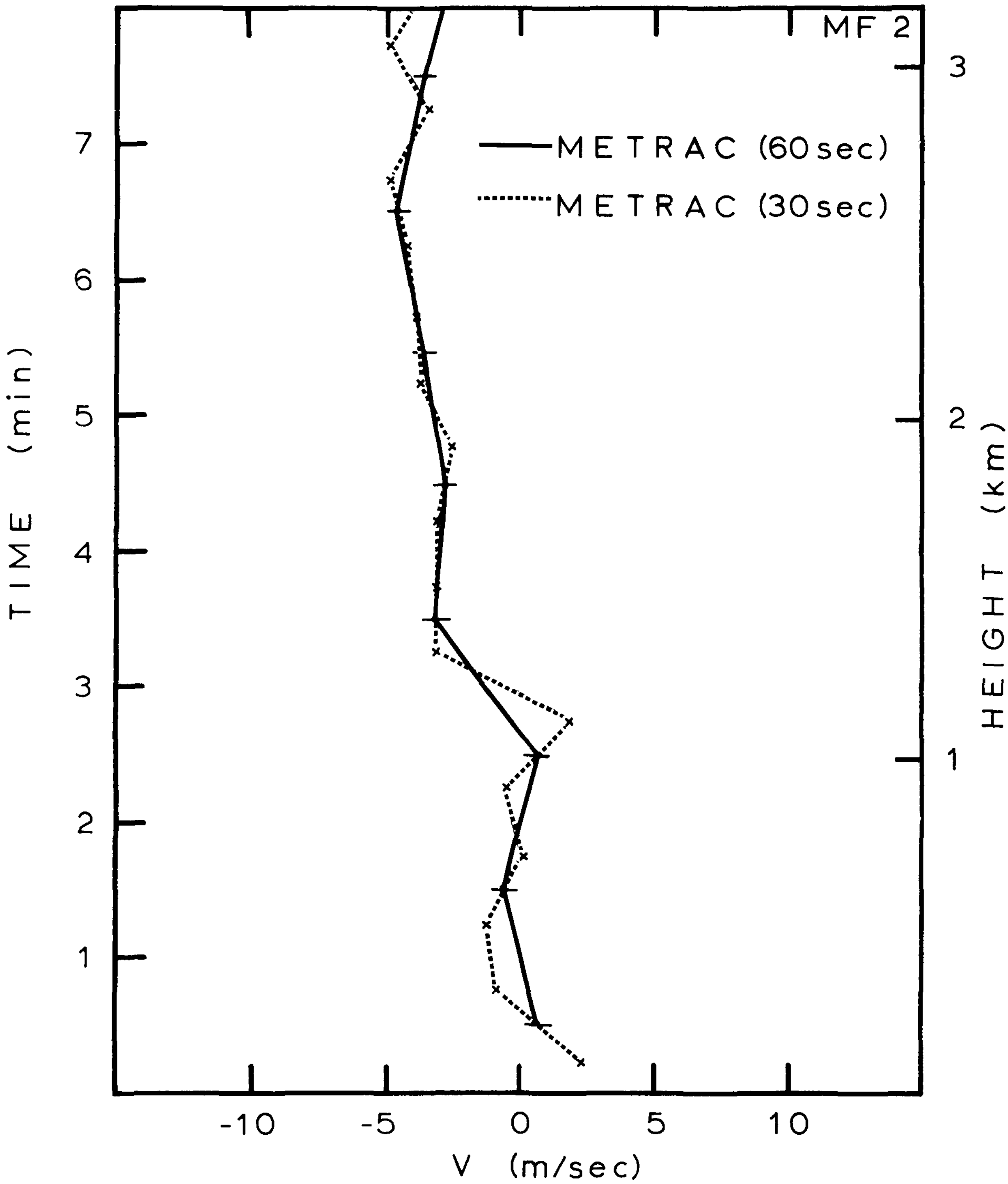


FIGURE 49. COMPARISON OF 60 SECOND AND 30 SECOND PROFILES

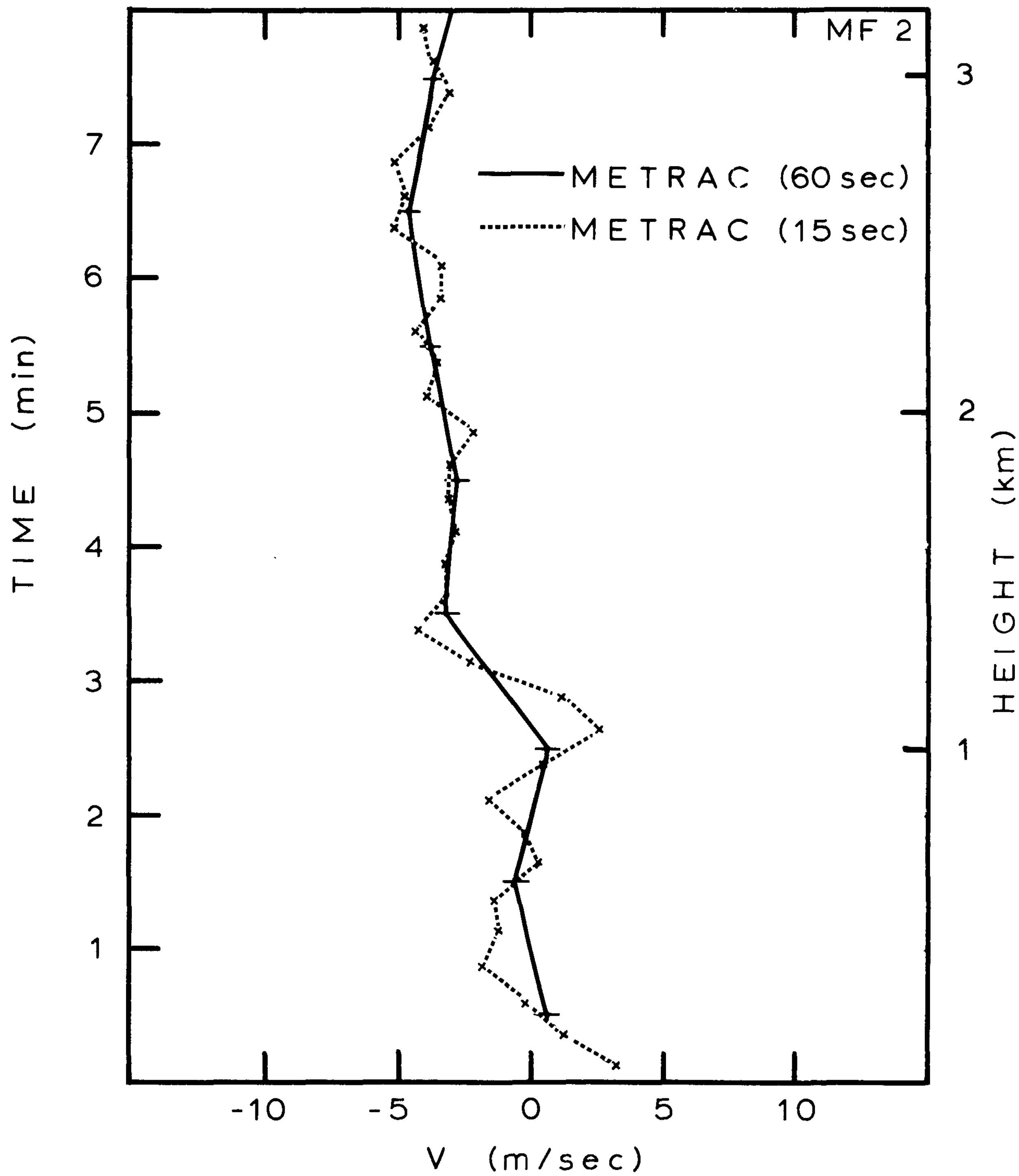


FIGURE 50. COMPARISON OF 15 SECOND AND 60 SECOND PROFILES (MF2)

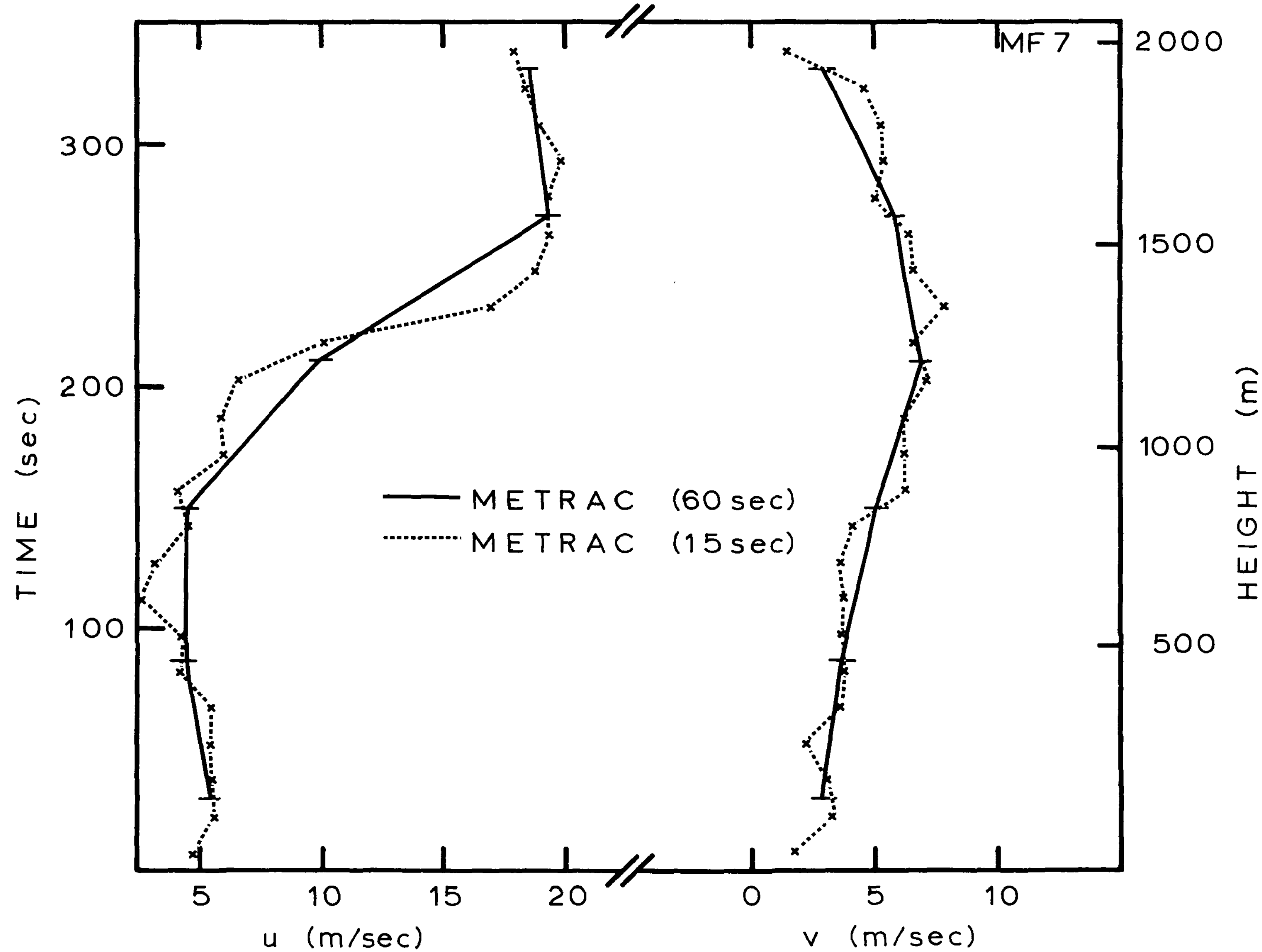


FIGURE 51. COMPARISON OF 15 SECOND AND 60 SECOND PROFILES (MF7)

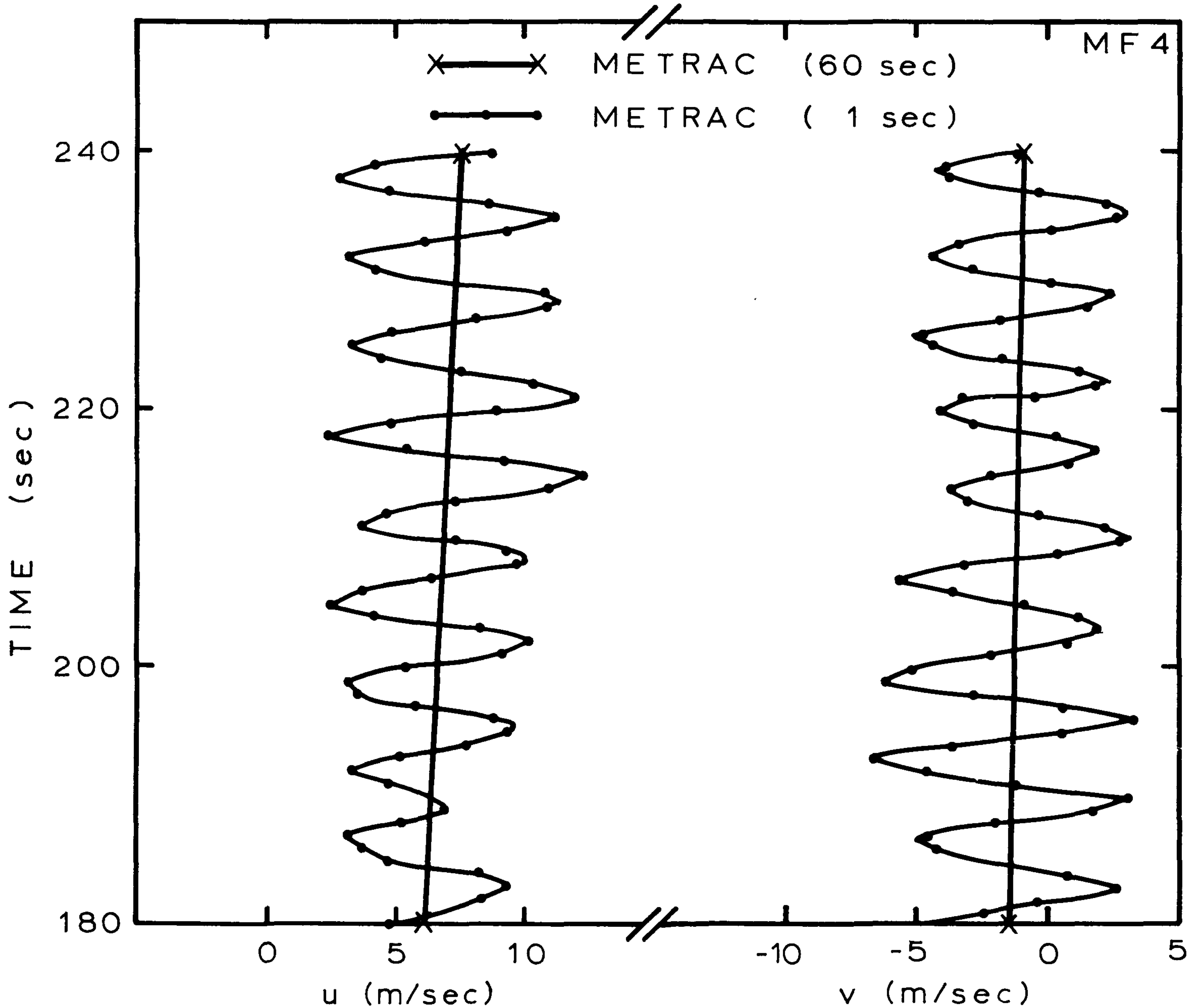


FIGURE 52. ONE SECOND SAMPLES FOR FLIGHT MF4 SHOWING OSCILLATION OF SUSPENDED TRANSMITTER

any assumption of balloon ascent rate or hydrostatic equilibrium. This feature combined with the high degree of resolution allows the possibility of measuring the atmospheric vertical motion. As an example, Figure 53 shows the variation in the vertical velocity of the balloon computed as ten-second averages plotted every thirty-seconds for METRAC flight MF1. The deviations of the computed balloon vertical velocity from the mean are very reasonable for real atmospheric vertical velocities.

The results of the Minneapolis field tests demonstrate that the METRAC system is capable of providing accurate winds on the micro and mesoscales, as well as on the synoptic scale. This provides a single flexible system which could be used for all atmospheric measurements such as, for example, diffusion and turbulence studies, regional air pollution programs, and synoptic analysis. Its application to such uses is anticipated.

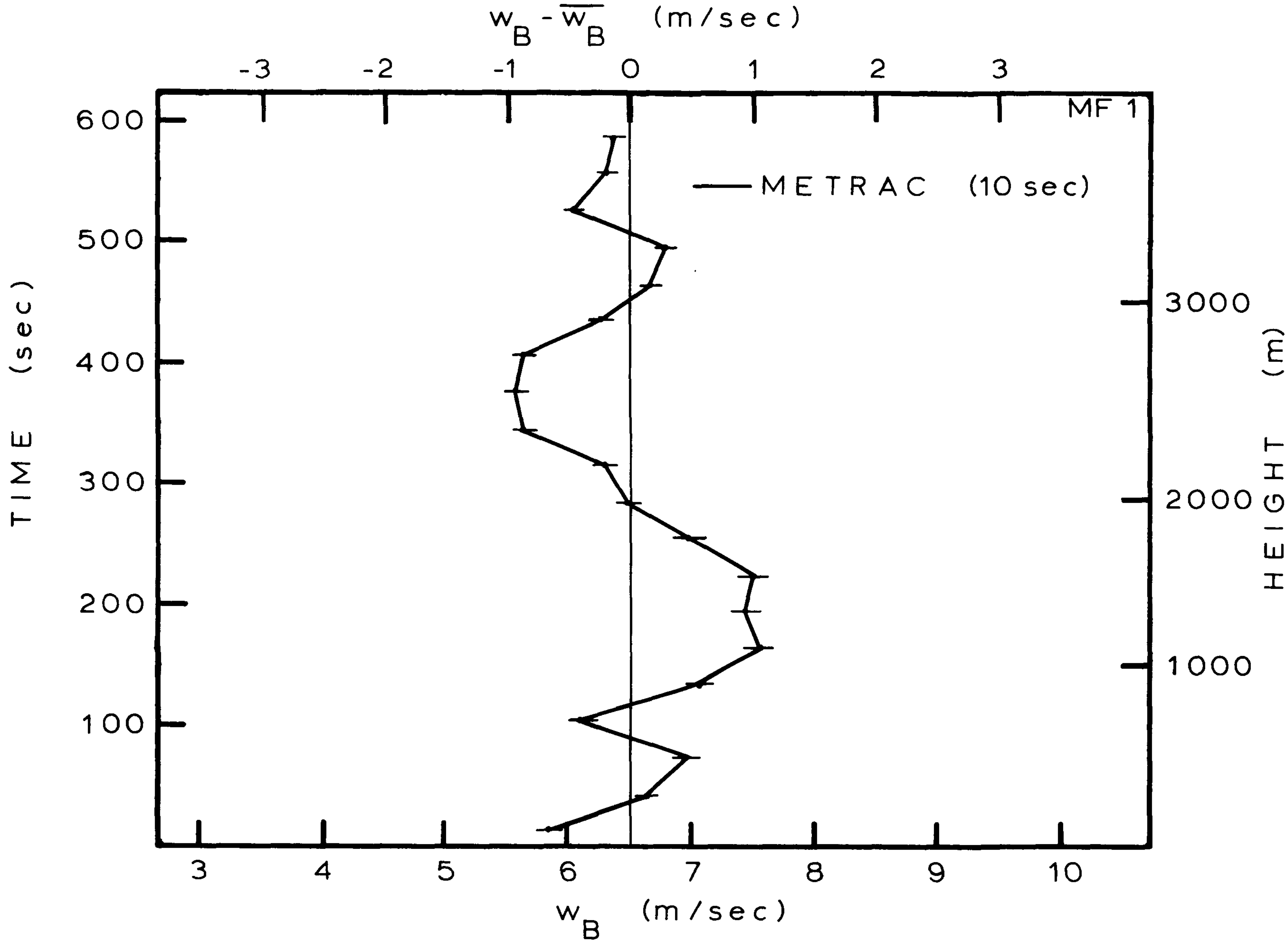


FIGURE 53. VERTICAL VELOCITY OF BALLOON VERSUS TIME AND HEIGHT

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